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Final Report

BUILDING HIGHWAY EMBANKMENTS OF FLY/BOTTOM ASH MIXTURES

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Indiana
Department
of Transportation

Purdue
University

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16. Abstract

This research investigates the engineering properties of mixtures of bottom ash and Class F fly ash relevant to their utilization in highway embankment construction. The research included ash samples from two major power plants in Indiana that disposed of their ash differently. The first power plant disposes of the bottom ash and fly ash separately and hence explicit mixtures were synthetically formed and tested. The second power plant disposes of the bottom and fly ash together in a common location and hence they become mixed, forming implicit mixtures. The implicit mixtures were processed using a wet method, the Shallow Slurry Deposition Method, to produce homogeneous samples for the research. Characterization of the ash included grain size analysis, specific gravity, maximum and minimum density, in addition to microscopic investigation. The investigation of compaction behavior of a range of explicit and implicit mixtures was conducted at the standard energy effort. The effects of changing the mixture composition on the maximum dry unit weight and optimum moisture content were established. In order to study the effect of changing the moisture content on penetration resistance, surface penetration tests were performed on the compacted samples. Beyond the optimum moisture content, the penetration resistance of the samples drops significantly, which suggests that the compaction can better be conducted dry of optimum. To control the compaction appropriately, the degree of compaction of a sample must be determined using a compaction curve for a mixture of similar gradation.

Consolidated drained triaxial tests were performed on a range of explicit and implicit mixtures at three levels of confining pressures. For each mixture tested, two groups of samples were prepared, one at a relative compaction (R%) of 90% and the other at 95%. The results indicate that the drained shear strength depends on the mixture composition, the degree of compaction, and the confining pressure. Adequate shear strength and volumetric behavior was observed for the samples compacted at 95%. It was concluded that the shear strength of the ash mixtures is comparable to the shear strength of sandy soils

Discussion and recommendations regarding the stability of slopes of ash mixtures is included. Using the critical state angles is more feasible in the slope stability analysis in the case of embankments of implicit mixtures due to mixture variability.

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LIST OF ABBREVIATIONS AND SYMBOLS

ASCE	American Society of Civil Engineers.
ASTM	American Society for Testing and Materials
c	Total strength intercept
c'	Effective strength intercept
CCBP	Coal Combustion By-Product
cm	Centimeters
DEM	Department of Environmental Management
DOT	Department of Transportation
EIA	Energy Information Administration
ENR	Engineering News Record
EP	Extraction Procedure
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
FHWA	Federal Highway Administration
FGD	Flue Gas Desulferization
IAC	Indiana Administrative Code
in.	Inch
INDOT	Indiana Department of Transportation
kN	Kilo Newton
kPa	Kilo Pascal = 1000 Newton per square meter
LM	Light Microscope
LOI	Loss on ignition
m	meter
N	Newton
NIPSCO	Northern Indiana Public Service Company
No.	Number
PaDER	Pennsylvania Department of Environmental Resources
PaDOT	Pennsylvania Department of Transportation
pcf	Pounds per cubic foot
PSI	Public Services Indiana
psi	Pounds per square inch
R	Relative compaction
SPT	Standard Penetration Test
SEM	Scanning Electron Microscope
TCLP	Toxicity Characteristics Leaching Procedure
u	pore pressure at a point
USDOE	United States Department of Energy
USIFCAU	University of Southern Indiana Forum for Coal Ash Utilization

VPM	Vibration per minute
σ'_1	Major principal stress
σ'_1	Axial stress in the triaxial test
σ'_3	Effective radial stress in the triaxial test
σ'_3	Minor effective principal stress
ϕ'	Effective angle of shearing resistance
ϕ'_{crit}	Critical angle of shearing resistance.
ϕ'_{max}	Peak angle of shearing resistance.
ε	strain
ε_a	Axial Strain
ε_v	Volumetric Strain

IMPLEMENTATION REPORT

This research is focused on the characterization of coal ash mixtures and investigation of their behavior in compaction and shear strength. Two types of coal ash mixtures were investigated in this research: explicit mixtures synthesized by mixing bottom ash (from a pond) with dry class F fly ash (from silos) at specific proportions and implicit mixtures (co-ponded ash) sampled directly from disposal sites. The utilization of the ash mixtures in highway embankment construction may provide a feasible alternative to their disposal. The success of this process depends on the mutual collaboration between the generators of coal ash and the INDOT.

The following recommendations are made available to INDOT to commence implementing the present research. The recommendations can also be useful to other applications that include compacted coal ash mixtures.

The interested coal ash producers can be invited to participate in a unified characterization process (developed by INDOT) composed of two parts:

A- The first part includes an environmental study for initial qualification of the existing ash mixtures in a power plant which may be potentialy used in highway embankment construction.

B- The second part includes the geotechnical characterization of the ash properties including grain size analysis, development of compaction curves and stress strain relationships for the range of mixtures existing in disposal sites.

CHAPTER 1
INTRODUCTION

1.1 Problem Statement

Embankment construction consumes large quantities of natural soils as structural fill. On the other hand, large quantities of coal ash are generated annually by the electric utility plants, which is a source of significant concern. Coal burning power plants in the United States produce, annually, over 75 million tons of coal combustion-by products (CCBP's), mostly fly ash and bottom ash (Srivastava and Collins 1989). The disposal of these huge amounts of waste presents a significant problem that faces the electric utility companies and the society in general. Recycling the coal ash by using it in large volume projects, such as highway embankments construction, represents one of the most promising alternatives to coal ash disposal.

Success of projects that made utilization of single types of coal ash has previously been demonstrated showing financial savings to both the highway agencies and the utility plants (Srivastava and Collins 1989; Brendel and Glogowski 1989; GAI and USIFCAU 1993). Unfortunately, most of the coal ash quantities generated in the state of Indiana are disposed in ponds in the form of mixtures, to minimize disposal costs. Accordingly, the coal ash mixtures have properties that depend upon the ash mixture composition. The complex behavior of the ash mixtures in compaction and shear strength need to be investigated. As the change in this behavior, due to changing ash mixture proportions, becomes understood, recommendations about the utilization of coal ash mixtures can then be developed.

More than 66% of the generated coal ash in the state of Indiana becomes disposed in mixtures (GAI and USIFCAU 1993). The ash types that are mostly disposed in this fashion are Class F fly ash and bottom ash. Until recently, the Indiana Department of

Transportation (INDOT) specifications of coal ash utilization, in highway construction, excluded the utilization of co-mingled ash from disposal ponds. The current special provisions allow only mixtures with fly ash content up to 35%. The major concerns are due to the control of their compaction and the shear strength of these mixtures. Huang (1990) also reported that the behavior of a bottom ash/fly ash mixtures is dependent upon the mixture proportion. The engineering properties of separated single types of ash were previously investigated (Huang 1990; Diamond 1985; Seals et al. 1972 ; DiGioia et al. 1986). Development of a standard guide for the use of coal combustion fly ash in structural fill was initiated (Brendel 1993). However, very limited laboratory and even less field data are available about the effects of mixture composition on the compaction and shear strength.

Embankment construction demands large quantities of materials as structural fill. The materials used as a structural fill must have adequate properties that survive as long as the embankment exists. Natural soils are commonly used for such a purpose. Meanwhile, the disposal of the large amounts of coal ash inflicts significant costs on the utility companies. These costs are normally transferred to the consumers. If large quantities of the coal ash can find utilization such as structural fills in embankments, the disposal problem can be reduced. Natural soils can thus be saved for more valuable uses. However, adequate compaction and stress-strain behavior needs to be demonstrated by the ash mixtures before they can be used as structural fill.

Adequate shear strength and low compressibility of the compacted material during service are among the most important factors required in a material used in highway embankment construction. Class F fly ash and bottom ash are cohesionless materials. The shear strength of these materials is mainly derived from the material composition, the state of compaction and the confining stresses. The hydraulic conductivity of these materials is normally similar to natural cohesionless soils, of similar gradations. Thus, they compress almost immediately under vertical loads. The control of compaction and the shear strength are the major concerns for design and construction. A well controlled experimental program is thus needed to investigate the behavior of the mixture.

1.2 Scope of this Study

The scope of this study is to investigate the compaction and shear strength behavior of coal ash mixtures to demonstrate their suitability for use in embankment construction. Environmental, physical and chemical investigations have previously been done for Indiana fly and bottom ashes (Diamond 1985; Huang 1990; Ke 1990). Both implicit and explicit mixtures of Class F fly ash and bottom ash are targeted for investigation in this research. These ash types were found most relevant for this research. The bottom ash and Class F fly ash are highly under-utilized and mostly disposed. Their relatively low market value makes them highly competitive to natural soils especially in large fill-volume projects.

The use of ash mixtures in the construction of highway embankments is a significant alternatives to disposal. Moreover, at the plants where the ash is disposed separately, it is useful to investigate if the mixtures can provide an enhanced engineering performance superior to a single ash type.

1.3 Research Approach

The objectives of this research are to study the compaction and shear strength behavior of fly/bottom ash mixtures as materials for embankment construction. To accomplish these objectives, a laboratory experimental program was designed and performed using coal ash from two power plants that disposed the ash differently. Two types of mixtures were implemented in this study: explicit mixtures were formed from mixing synthetically composed bottom ash with class F fly ash from power plant A, and implicit mixtures consisted of processed samples from power plant B.

Initial surface samples followed by large, deeper samples, were extracted at the two power plants aiming at an appropriate representation of the range of mixtures at the disposal sites. Visual examination was performed using the naked eye, a light microscope and a scanning electron microscope to study the shape and surface of the ash particles. Earlier studies on these plants' ashes included chemical analysis, X-ray diffraction, soundness, degradation, permeability, and CBR (Diamond 1985; Huang 1990; Ke 1990; Bhat and Lovell 1996). In this study the characterization tests included

determination of grain size distribution, and specific gravity tests. It also included microscopic examinations using low magnifications and high magnification (scanning electron microscopy SEM) microscopy.

The ash was processed to form samples from the mixtures. Synthetic mixtures were then constructed, mixed, moistened, and compacted. Each mixture had a characteristic compaction curve. A family of compaction curves was generated from the compaction curves of the mixtures. The mixtures were tested in consolidated drained (CID) triaxial compression tests at two compaction levels to investigate their characteristics in compressibility and shear strength. The testing program provided information about the change in behavior with respect to changes in the fly-bottom ash proportions. The results are discussed and explained with consideration to the utilization of the material in embankment construction. The results can be useful for assessing the effects of utilization of a range of ash mixtures and the impacts on the control of compaction.

1.4 Outline of this Thesis

Chapter 2 furnishes background about the coal ash generation, types (Class F fly ash, Class C fly ash, bottom ash, and boiler slag), composition, disposal, and utilization. An overview of the engineering properties of the ash with consideration to their relevance to embankment construction is presented. The different concerns regarding the coal ash utilization in embankments are also discussed including the environmental, economic concerns and the performance concerns. Special considerations in design and construction are discussed. Some examples from previous experiences in ash utilizations are included.

Chapter 3 explains the experimental program followed in this study. Sampling procedures are outlined. Ash processing for the development of ash mixture samples is explained. The characterization tests including grain size distribution, microscopic examination, and specific gravity tests are described. The procedures implemented for the compaction of the samples, the construction of compaction curves, and the laboratory penetration tests are summarized. The equipment and procedures utilized in the triaxial tests are also explained in chapter 3.

Chapter 4 summarizes the results of the compaction of different ash mixtures. Discussion of the effects on the compacted dry density, due to changing the mixture composition and the compaction moisture content, is included. The effects of changes in the moisture content on the penetration resistance are discussed.

Chapter 5 summarizes the results of the shear tests using the triaxial procedures. The axial stress and volumetric strain versus axial strain are presented for the explicit and implicit ash mixtures. The effects of mixture compositions on the peak and critical angles of shearing resistance are explained. The volumetric behavior during consolidation and shear are discussed.

Chapter 6 presents the application of the results of this research to embankment construction and design. Considerations related to the use of ash mixtures in embankment construction are addressed. Chapter 6 also includes a discussion of the stability of slopes and embankment performance. It also includes an examination of the impact of the current disposal practices on the large volume utilizations and address the needs for improving theses practices.

Chapter 7 recapitulates the conclusions of this research and summarizes the recommendations for future research.

CHAPTER 2
COAL ASH GENERATION, DISPOSAL, CHARACTERISTICS, AND UTILIZATION

2.1 Coal Ash Generation and Composition

2.1.1 Coal Ash Generation in the United States and Indiana

Coal combustion produces fly ash (Class C and Class F), bottom ash, boiler slag (Black Beauty), and flu gas desulferization materials (FGD or scrubber sludge) as by-products. Coal is one of the major fuels for electricity production. According to the United States Department of Energy records, about 800 million tons of coal are burned annually in electric utility plants in the United States (EIA 1994b). Each type of coal contains non-combustible materials that represent the main composition of the ash. Approximately, 10% of the coal burned turns into ash. Some lignite coal contains 30% of its composition as non-combustible matters (Huang 1990). Over the past four decades, trends of coal consumption by electric utilities has shown no decrease as illustrated in Figure 2.1 (EIA 1994a). The increasing demand for electric power has led to a continuous increase in the coal use. Availability of coal sources in the United States plays a major role in these trends. The recent developments in increasing coal burning efficiency has not led to an actual reduction in the coal quantities burned, while the advances in air pollution control technologies have increased the waste generation by the utility companies.

More than 98 % of the total electric power developed in Indiana was generated using coal as a fuel. Ranked fourth after Ohio, Texas and Pennsylvania, Indiana has generated 95,746 million kilowatt-hours from coal fueled electric utilities in 1992 (EIA 1994c). Accordingly, Indiana is one of the major coal ash generators in the United States.

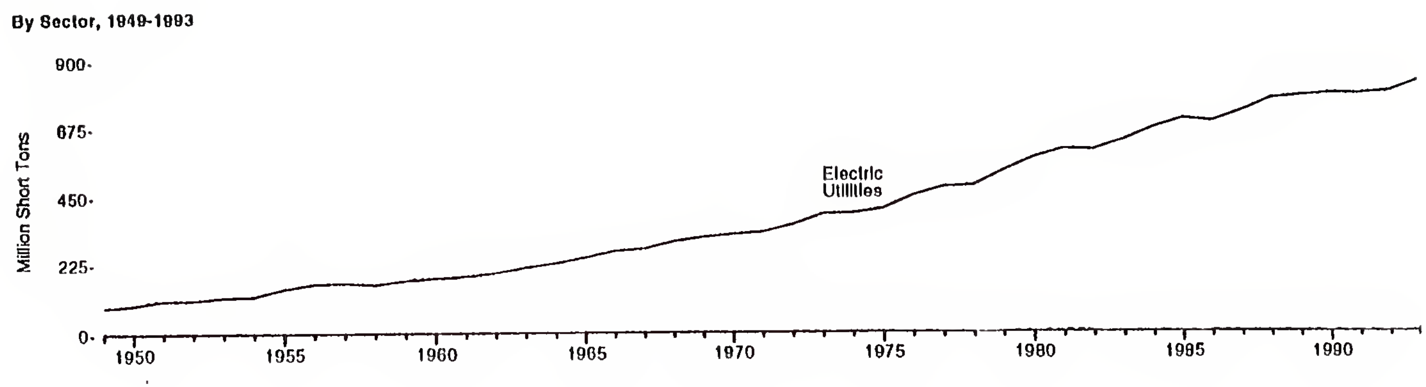


Figure 2.1 Trends of Coal Consumption by the Electric Utilities in the United States (1949-1993). (EIA 1994a)

A recent study of ash generation and utilization in Indiana indicates that more than six million tons of coal combustion by products (CCBP) are generated annually. Table 2.1 displays the CCBP's annual production in Indiana by plant. The numbers were based on quantities reported by utilities as a response to a questionnaire. They indicate that huge amounts of by-products are generated. Out of the total quantity of CCBP's, more than four million tons of fly ash (Class C and Class F) and bottom ash were generated. Most of the coal ash in Indiana is treated as a waste. Utilization of the ash reduces the disposal problem significantly. Huge quantities of ash are accumulated over time at disposal sites. Recent studies have shown alternative possibilities for utilization of ash in highway embankment construction.

2.1.2 Fly Ash Generation and Composition

Fly ash is generated as one of the by-products of coal combustion. It consists of fine-grained, light-weight material that has grain sizes ranging between fine silt and fine sand. The fly ash particles are carried off in the hot gas stream due to their very small particle sizes and relatively large surface area. The fly ash particles are then collected by the air pollution control equipment. Fly ash grains are composed of the noncombustible mineral matters in the coal plus the carbon that remains unburned after combustion. They are mainly composed of oxides of silicon, aluminum, iron, and calcium (EPA 1988). Other minor ratios of potassium oxide (K_2O), sodium oxide (Na_2O), magnesium oxide (MgO), titanium oxide (TiO_2), phosphorous pentoxide (P_2O_5), and sulfur trioxide (SO_3) may also exist in the grain composition. These compounds of oxides may interchangeably be existing in the ash in the form of sulfates, and/or silicates. Small quantities of phosphates and trace elements may also exist in the formation of the fly ash grains. Features of the trace elements existing in the coal ash are discussed in further detail in Section 2.4.2.

Two types of fly ash may be generated, namely class C and class F fly ashes. Class C fly ash results from burning subbituminous or lignite coals, while burning bituminous or anthracite coals generates class F fly ash. Class F fly ash has pozzolanic properties.

Table 2.1 Coal Combustion By-Products (CCBP's) Quantities and Types Generated by Power Plants in the state of Indiana.
(GAI and USIFCAU 1993) (NT = Not Tested) (CCBP types are according to 329 Indiana Administrative Code)

Plant	Class C Fly Ash Quantity tons/yr.	Type	Class F Fly Ash Quantity tons/yr.	Type	Bottom Ash Quantity tons/yr.	Type	Boiler Slag Quantity tons/yr.	Type	FGD Material Quantity tons/yr.	Type	Total CCBPs Quantity tons/yr.
Vincennes District											
Breed	-	-	8,200	1	-	-	19,000	4	-	-	27,200
Rockport	331,000	1	-	-	142,000	3	-	-	-	-	473,000
Gibson	-	-	640,000	2	153,000	3	-	-	226,000	2	1,019,00
Petersburg	-	-	301,400	NT	75,400	3	-	-	456,800	3	833,600
Edwarsport	-	-	7,900	2	1,900	2	-	-	-	-	9,800
Ratts	-	-	50,000	3,4	12,000	4	-	-	-	-	62,000
Merom	-	-	280,000	3	30,000	3,4	-	-	360,000	3,4	670,000
Brown	-	-	88,000	2,3	22,000	-	-	-	180,000	3	290,000
Culley	-	-	88,000	2,3	22,000	-	-	-	-	-	110,000
Warrick	-	-	200,000	2,3	50,000	3	-	-	-	-	250,000
Jaspor	-	-	-	-	12,000	4	-	-	-	-	12,000
G. E. Plastics	-	-	27,850	3	10,120	3	-	-	-	-	37,970
Total	331,000		1,691,350		530,420		19,000		1,222,000		3,794,570
Crawfordsville District											
Cayuga	-	-	223,000	2	56,000	3	-	-	-	-	279,000
Wabash	-	-	120,000	3	30,000	4	-	-	-	-	150,000
Total	-		343,000		06,000		-		-		429,000
LaPorte District	-										
Schahfer	10,900	NT	163,000	NT	127,800	NT	-	-	309,100	NT	610,800
Mitchell	75,400	NT	-	-	17,400	NT	-	-	-	-	92,800
Baily	-	-	41,000	NT	86,800	NT	-	-	-	-	127,800
Michigan City	-	-	33,000	NT	77,100	NT	-	-	-	-	110,100
State Line	20,000	3	-	-	1,200	3	9,300	4	-	-	30,500
Total	106,300		237,000		310,300		9,300		309,100		972,000
Seycamour District	-										
Tanners Creek	-	-	69,000	NT	10,000	NT	46,000	4	-	-	125,000
Gallagher	-	-	76,000	2	20,000	3	-	-	-	-	96,00
Clifty Creek	-	-	194,000	3		-	240,890	4	-	-	434,890
Total	-	-	339,000		30,000		286,890		-		655,890
Greenfield District											
Pritchard	-	-	17,200	NT	4,300	NT	-	-	-	-	21,500
Perry	-	-	27,920	NT	6,900	NT	-	-	-	-	34,900
Stout	-	-	75,000	NT	18,700	NT	-	-	-	-	93,700
Noblesville	-	-	4,100	3	1,000	4	-	-	-	-	5,100
Whitewater	-	-	19,500	2	4,875	2	-	-	-	-	24,375
Total	-	-	143,720		35,855		-	-	-		179,575
Total	437,300		2,754,070		992,575		315,190		1,531,900		6,031,035

The name "pozzolan" is derived from terminology used by the Romans' to describe a volcanic ash deposit at Pozzuoli (Ingles and Metcalf 1972). The pozzolans are "*siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties*" (ASTM C 618-91). Mineralogical analysis reveals that the chemical constituents of the ash exist in crystalline form or as a glass. Crystals of quartz, magnetite, and hematite may exist in the fly ash. The typical glass content in fly ash ranges between 66 and 88% (DiGioia and Brendel 1992). Carbon content in the ash is usually measured by weight loss on ignition (LOI). A high carbon content may inhibit pozzolanic reactions. An efficient power plant may have values of LOI as low as 3%.

Class F fly ash is a pozzolanic material which needs adding both lime and water to develop cementitious reactions. Sheu et al. (1990) reported data from testing Class F fly ash generated using bituminous coal from the USA, Australia, and South Africa. Table 2.2 displays the chemical composition of the fly as. The results show that chemical composition was very slightly affected by the grain size. The loss on ignition (LOI) was noticeably higher for the coarse fly ash retained on sieve no.200. They reported that the pozzolanic activity increases as the grain size decreases.

Due to the presence of lime Class C fly ash has cementitious properties in addition to its pozzolanic properties Accordingly, chemical reactions develop in the presence of water and lead to the formation of chemical components at hydration similar to those developed by the hydration of portland cement.

2.1.3 Bottom Ash And Boiler Slag Generation and Composition

Bottom ash is composed, similar to the fly ash, from the noncombustible portion of the coal plus some carbon from the residual unburned coal (Huang 1990). Whereas smaller ash grains go up the stack with the flu gases in the form of fly ash, the larger grains are accumulated on the heat absorbing surfaces of the furnace. Gradually, excess amounts of the larger grains fall into hoppers or conveyors at the bottom of the furnace.

Table 2.2 Chemical Composition and Pazzolanic Activity Index of Sieved Fly Ash (Sheu et al. 1990)

Items	Original fly ash	Fly Ash Retained 200 mesh	Fly Ash Passing 200 mesh	Fly Ash Passing 300 mesh	Fly Ash Passing 400 mesh
Chemical Composition					
Ignition Loss (%)	7.01	20.0	6.24	5.24	3.00
SiO_2 (%)	47.33	44.3	47.65	48.14	48.76
Al_2O_3 (%)	24.88	16.77	23.35	25.77	28.78
Fe_2O_3 (%)	7.14	6.99	7.91	8.26	6.84
CaO (%)	8.21	7.99	9.44	8.25	7.75
MgO (%)	1.45	1.25	1.56	1.47	1.24
$K_2O + Na_2O$(%)	1.21	0.60	1.26	0.99	1.14
TiO_2 (%)	1.34	0.50	1.01	1.40	0.63
SO_3 (%)	0.46	0.81	0.38	0.45	1.35

The ash particles are either solid or partially molten. As the particles cool down in dry conditions, they form bottom ash particles. If the furnace temperature is high enough, the bottom ash is in a molten state, either partially or totally. As the molten ash is collected and quenched into water it forms glassy type particles that are called boiler slag. The bottom ash is usually passed through a crusher after generation to reduce the particle sizes before entering the disposal system.

The most common types of furnaces are the pulverized coal furnaces, the cyclone furnaces, and the stoker furnaces in the United States. Pulverized-coal furnaces with dry bottom or wet bottom are the most widely used types. A dry bottom normally generates bottom ash since the ash leaves the boiler in a solid state. If the ash leaves the boiler in a molten state, the boiler has a wet bottom. Cyclone furnaces reach very high temperatures exceeding 1650°C (3000°F) which is high enough for the ash to be collected in a completely molten condition. The cyclone furnaces are wet bottom furnaces, normally generating 70 to 85% of the total ash as boiler slag. Only 15 to 30% of the ash flow through the top of the boiler with the flu gases as fly ash.

Stoker-Fired furnaces usually produce coarser bottom ash grains than those produced by pulverized-coal furnaces or cyclone furnaces. The ratios of ash types generated from the Stoker furnaces vary based on their type. Some of the bottom ash generated by Stoker-fired furnaces are of lower quality than others. Fragile popcorn like bottom ash may be generated by some types of stoker boilers (Huang 1990).

2.2 Coal Ash Disposal Practices in Indiana

The disposal of immense amounts of coal ash is a serious problem that faces electric utility plants, and society in general. The costs associated with ash disposal are also high. In the 1980's, the estimated costs for ash disposal in the USA ranged from $375 million to $740 million (ENR 1980). These numbers have increased in the 1990's. The rates of consumption of coal ash are still far behind the rates of generation. Table 2.3 displays the United States coal combustion by-products (CCBP's) production and consumption. The greater portion of the ash produced is largely disposed. The US Environmental Protection Agency (EPA) has delegated the management of CCBP's

disposal and utilization to the state's environmental departments. In general the states departments of environmental management (DEM's) manage CCBP's disposal under EPA's solid waste disposal regulations, Subtitle D of the Resource Conservation and Recovery Act (RCRA) (EPA 1990).

Most of the bottom ash and Class F fly ash are disposed, mainly because of their low market value and the lack of large volume utilization practices. About 3 million tons of ash are disposed annually in Indiana [the flue gas desulferization (FGD) materials are not included in these numbers]. Table 2.4 summarizes the current CCBP disposal rates and methods in Indiana.

Coal ash is disposed using either a dry method or a wet method. Using the dry method, the ash is stored dry in silos or in large piles then loaded into trucks and transported to a disposal site, a landfill, where it is finally placed. The ash is then compacted to reduce its permeability. To minimize the potential for outflow of leachates, encasement of the ash is required to minimize infiltration of rain inside the fill and to impede the outflow. A system of a hydraulic barrier, and a leachate collection system are normally used for this purpose. The hydraulic barrier is either made of a low permeability soil layer or a synthetic membrane. The leachate collection system can be made of soil filter or synthetic filters. Combinations of these barriers and filters may also be used to minimize any leachate transport out of the fill. This method of disposal is usually used by power plants located in urban areas where the availability of land is limited. The cost associated with the dry method is somewhat higher than that of the wet method.

Most of the ash disposal in Indiana is performed using the wet method. As shown in Table 2.4, this is how the majority of the ash is disposed. Using the wet method, the ash is mixed with large quantities of water to form a slurry. The slurry is conveyed hydraulically through pipelines to disposal ponds. Some power plants may have a special disposal pond for each type of ash. Other power plants may convey the different types of ash through separate pipelines but dispose them all in a single location where they become mingled.

Table 2.3 Coal Combustion By-Products (CCBPs) Quantities and Types Generated in the United States (in Tons)
(GAI and USIFCAU 1993)

CCBP Type	Produced	Consumed	Percent
Fly Ash	48,931,722	12,420,163	25.4%
Bottom Ash	13,705,653	5,360,104	39.1%
Boiler Slag	5,234,316	3,252,220	62.1%
FGD Material	18,932,688	215,852	1.1%

Table 2.4 The Methods and Rates of Coal Ash Disposal in The State of Indiana. (GAI and USIFCAU 1993)

Plant	Bottom Ash[b]	Ponded Ash[c]	Landfilled Ash[d]	Landfilled Boiler Slag
Vincennes District				
Breed	0	0	8,200	0
Rockport	121,000	0	130,000	0
Gibson	0	643,000	0	0
Petersburg	0	164,800[e]	0	0
Edwardsport	0	9,800	0	0
Ratts	12,000	50,000	0	0
Merom	0	0	0	0
Brown	0	110,000[e]	0	0
Culley	0	110,000[e]	0	0
Warrick	0	250,000	0	0
Jasper	12,000	0	0	0
G. E. Plastics	0	0	38,000[e]	0
Total	145,000	1,337,600	176,200	0
Crawfordsville District				
Cayuga	0	279,000	0	0
Wabash	0	150,000	0	0
Total	0	429,000	0	0
Laporte District				
Schahfer	127,800	0	0	0
Mitchell	0	0	0	0
Bailly	0	0	0	0
Michigan City	26,000	0	0	0
State line	0	0	9,200	0
Total	153,800	0	9,200	0

Contintued, Table 2.4

Seymour District				
Tanners Creek	10,000	69,000	0	0
Gallagher	0	96,000	0	0
Clifty Creek	0	0	194,000	149,000
Total	10,000	165,000	194,000	149,000
Greenfield District				
Pritchard	0	21,500	0	0
Perry	0	0	34,900	0
Stout	0	93,700	0	0
Noblesville	0	5,100	0	0
Whitewater	0	0	24,400[e]	0
Total	0	120,300	59,300[e]	0
Total	308,800	2,051,900	438,700	149,000

[a]Does not include FGD material, by-products co-disposed with FGD material, or by-products disposed of in a Type I landfill.
[b]Bottom ash ponded or landfilled separately from fly ash.
[c]Fly ash ponded alone or co-ponded fly ash and bottom ash.
[d]Fly ash landfilled seperately or with bottom ash.
[e]Assumed co-disposal of fly ash and bottom ash.

Gradually, the disposal ponds are filled with ash deposits and less space for disposal becomes available. The displaced water is normally flowed to a cooling pond.

As a pond becomes filled with ash, it is usually closed using a cover of soil and vegetation while the disposal is directed to another pond site. This method of disposal consumes large tracts of land that can otherwise be used more efficiently. This problem can be minimized if the ash utilization rates were high enough to consume the ash as it accumulates.

Developing new methods for disposal and improving the current disposal practices may provide some potential for decreasing the disposal problem. In Canada, Ontario Hydro owned and operated the large Natiocoke facility and developed a management plan for its ash disposal facility. The coal ash was initially disposed in a large pond. Accumulations of ash developed a very mildly sloped fan shaped delta around the disposal outlets. The ash deposit was too soft for machinery to operate on its surface. An alternative to direct deposit in the pond was developed. The disposal pipes were directed to discharge the ash slurry in settling cells that were routinely dredged. The dredged ash was piled on top of the soft deposited ash in the main pond. The ash was piled in mounds that reached 10 m (30 ft) high. Problems such as stability of slopes founded on loose ash, use of ash for building water retaining dikes, construction vehicles mobility on loose lagoon ash, dust control, seepage, winter operation, and design of long term ash storage mounds, had to be dealt with. These problems were solved successfully using a combination of engineering practices and field experience (Chan and Cragg 1987). Nevertheless, high piling of the ash only increases the capacity of a disposal site rather than solving the disposal problem. Solutions that aim at increasing the capacity of disposal sites offer a short term solution to disposal problems. Gibson power plant, Indiana, constructed a third disposal site after filling one completely and nearly filled the second site. Unless sufficient ash consumption takes place, any disposal site may eventually run out of space. If the ash continues to be disposed at the current rates, more costs will be inflicted on the power-generation process, which are then, transferred to the end consumer.

2.3 Engineering Properties of Coal Ash

2.3.1 Physical Characteristics

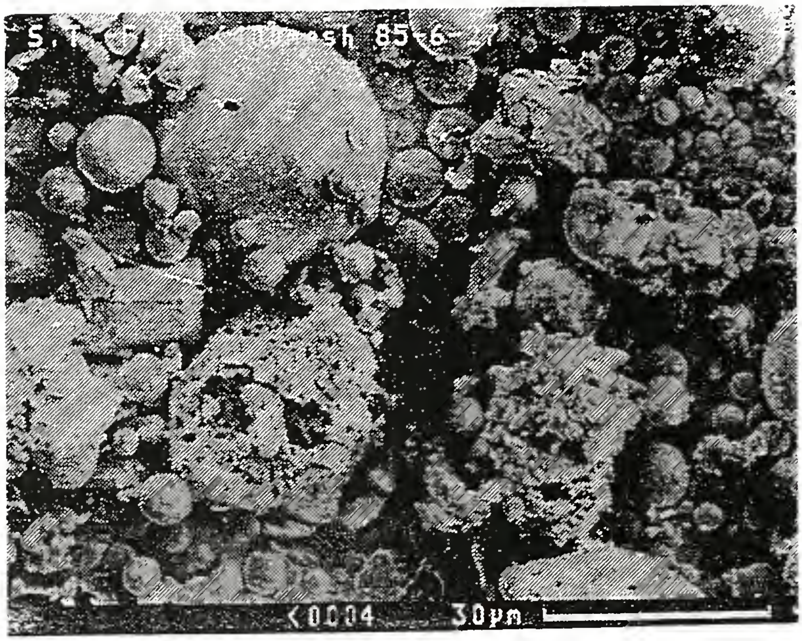
2.3.1.1 Appearance

The appearance of the ash materials differs based upon the type. Fly ash is a powder like material. Fly ash particles are barely visible to the naked eye. Under magnification, fly ash particles appear to be mostly spherical in shape (Diamond 1985). Some of the particles are broken and some are hollow. Most of the particles with diameters below 0.005 mm appear to be spherical. Figures 2.2 (a,b) display micrographs of fine and coarse Class F fly ash particles (Sheu et al. 1990). The coarser fly ash particles appear to include some non-spherical particles. The color of fly ash ranges between gray to greenish gray depending upon the chemical composition of the ash particles. Diamond (1985) reported that some fly ash particles are actually colorless and some have very dark color. The color of the fly ash aggregate is the result of the combined effect of the various colored and colorless individual particles rather than a single color of all particles. Dry fly ash is hard to handle. It can be disturbed easily forming dust. Moistened fly ash develops apparent cohesion similar to silty soils. As the moisture content increases the fly ash color becomes darker. If the moisture content increases sufficiently fly ash forms a dark slurry.

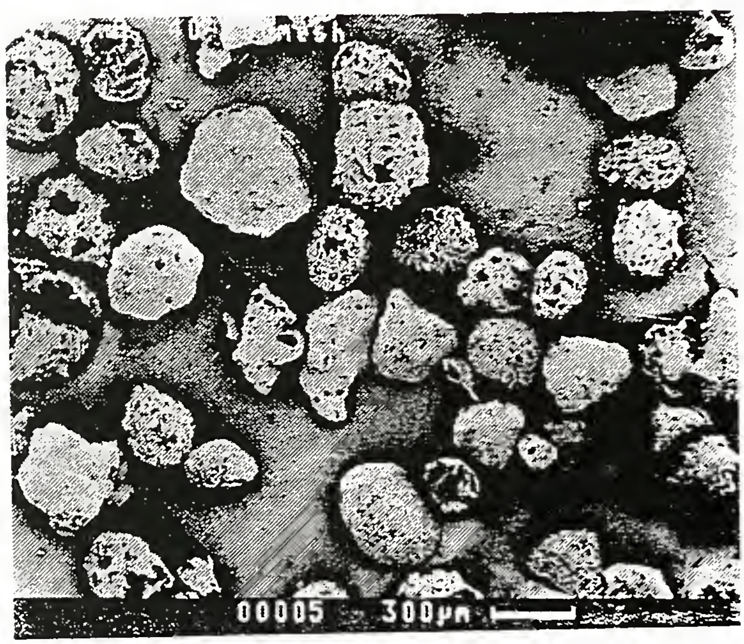
Bottom ash particles are coarser than the fly ash particles. The particles are angular with colors ranging from gray to black, their surfaces are rough porous and dull (Huang 1990). Angularity promotes interlocking and roughness resists inter-particle sliding.

Boiler slag (wet bottom ash) grains are hard, shiny, black, angular to sub-angular particles. Coarser particles are more porous. Some particles may be rounded or rod-shaped (Huang 1990). Slags from lignite and sub-bituminous coals tend to be more vesicular than slags of the eastern bituminous coal (Huang 1990).

If the boiler slag is developed with bottom ash it may contain easily breakable large particles. At some power plants (e.g. Gibson Plant and Schahfer Plant, Indiana) the bottom ash and boiler slag are run through a crusher to reduce their aggregate size.



(a) Passing no.400 Sieve.



(b) Retained no.200 Sieve.

Figure 2.2 Scanning Electron Microscopic Photos of Class F Fly Ash:
(a) Passing No.400 Sieve, (b) Retained on No. 200 Sieve.
(Sheu et al. 1990)

They are then flushed with water and driven through the disposal pipes. As a result of the crushing process, the particle shapes become more angular.

2.3.1.2 Specific Gravity

The specific gravity of ash is affected by the chemistry and structure of the individual particles. The iron content in ash particles increases the specific gravity. For particles with similar chemical composition, the particles with solid structures tend to have greater specific gravities than the particles with hollow and porous structures (Huang 1990).

Fly ash particles normally have specific gravities that range between 2.1 to 2.9. (Diamond 1985 ; GAI and USIFCAU 1993). The upper values in the range of specific gravities is usually observed when iron is present in the coal. Lignite coal, typically high in iron, generates Class C fly ash with relatively high specific gravity, ranging from 2.5 to 2.9. Sub-bituminous coal burning develops Class C fly ash with specific gravities ranging from 2.1 to 2.6. The specific gravity of Class F fly ash formed from burning of bituminous coal ranges between 2.3 and 2.6. Diamond (1985) used four different methods to determine the specific gravity of each one of 14 fly ashes of different Classes. All of the methods were based on pycnometery. Liquid pycnometric fluids, kerosene and mercury, were used in two methods. The other two methods involved measurements in nitrogen gas and helium gas (Diamond 1985). The inconsistency between the results of the four methods was referred in part to the difficulty of voluntary fluid entrance into the tiny inner voids of the fly ash. This is still an area of research on its own and most of the methods used in that study are not common in most laboratories. More data are needed to evaluate the results from the different methods.

The bottom ash particles tend to have specific gravity values that are less than natural granular soils. Like the fly ash, bottom ash's specific gravity increases as the iron content in the coal increases. Normally, the specific gravity of bottom ash particles ranges between 2.0 and 2.6. Fragile popcorn bottom ash particles may have a specific gravity value as low as 1.6 (Anderson et al. 1976). Boiler slag is more likely to have specific gravities, higher than bottom ash, ranging from 2.6 to 2.9 with an average of

2.75. Table 2.5 displays the specific gravity of bottom ash sampled from Indiana power plants using three different procedures. It can be easily noticed that the specific gravities determined using the gas pycnometer were somewhat higher than the liquid pycnometer. It was reported that, similar to the fly ash condition, gas molecules penetrated through the very tiny voids and filled the more unaccessible to reach voids of bottom ash.

2.3.1.3 Grain Size Distribution

The typical ranges of grain size distribution for fly ash, bottom ash, and boiler slag are displayed in Figure 2.3 (GAI and USIFCAU 1993). The sizes of the particles range from the coarse gravel size to the coarse clay size particles.

The fly ash particle size ranges between 0.6 mm (No. 40 sieve) to 0.001 mm. This range spans the sizes of fine sands, silt, and coarse clay particles. Fly ash grain size analysis is typically carried out either using some type of deposition method that implements Stoke's law of viscosity or using sieves with very fine meshes. In the deposition methods, the diameter of sedimenting particles are found at elapsing time intervals. The idea is that coarser size particles will be deposited faster than the smaller-in- size particles. This method assumes that the sedimenting particles are spherical in shape, which is a reasonable approximation in the case of fly ash. Very fine meshes can also be used for grain size analysis of fly ash. Sheu et al. (1990) reported that most of the Class F fly ash, investigated, passed through No.400 sieve (0.0325 mm). Only less than 6% were retained on no. 200 sieve (0.075 mm).

Crushed bottom ash is a well graded material. The particle size range typically falls between 25.4 mm (1 inch) to 0.075 mm (sieve #.200). The fines content ranges between 0% and 10 % but those fines are in general nonplastic. Boiler slag grain size distribution is more uniform. The majority of the particles fall in sizes ranging between 10 mm and 0.6 mm (No. 30). Some oversize particles may exist. The ASTM standards (D 422-90), for particle size analysis, are typically used.

Table 2.5 Specific Gravity of Bottom Ash Samples From Indiana Power Plants (Huang 1990)

Ash Source	ASTM C 128[a]	ASTM D 854[b]	Gas Pycnometer
Schahfer			
Unit 14	2.81	2.82	2.83
Unit 17	2.47	2.57	2.61
Mitchell	2.35	2.44	2.57
Gibson	2.50	2.55	2.74
Gallagher	3.05	3.07	3.10
Wabash	2.45	2.56	2.56
Brown	2.70	2.74	2.75
Culley	3.20	3.21	3.19
Richmond	2.79	2.90	2.89
Perry	1.84	2.12	2.32
Stout	3.43	3.46	3.50

[a] Standard test method for specific gravity and absorption of fine aggregate.
[b] Standard test method for specific gravity of soils.

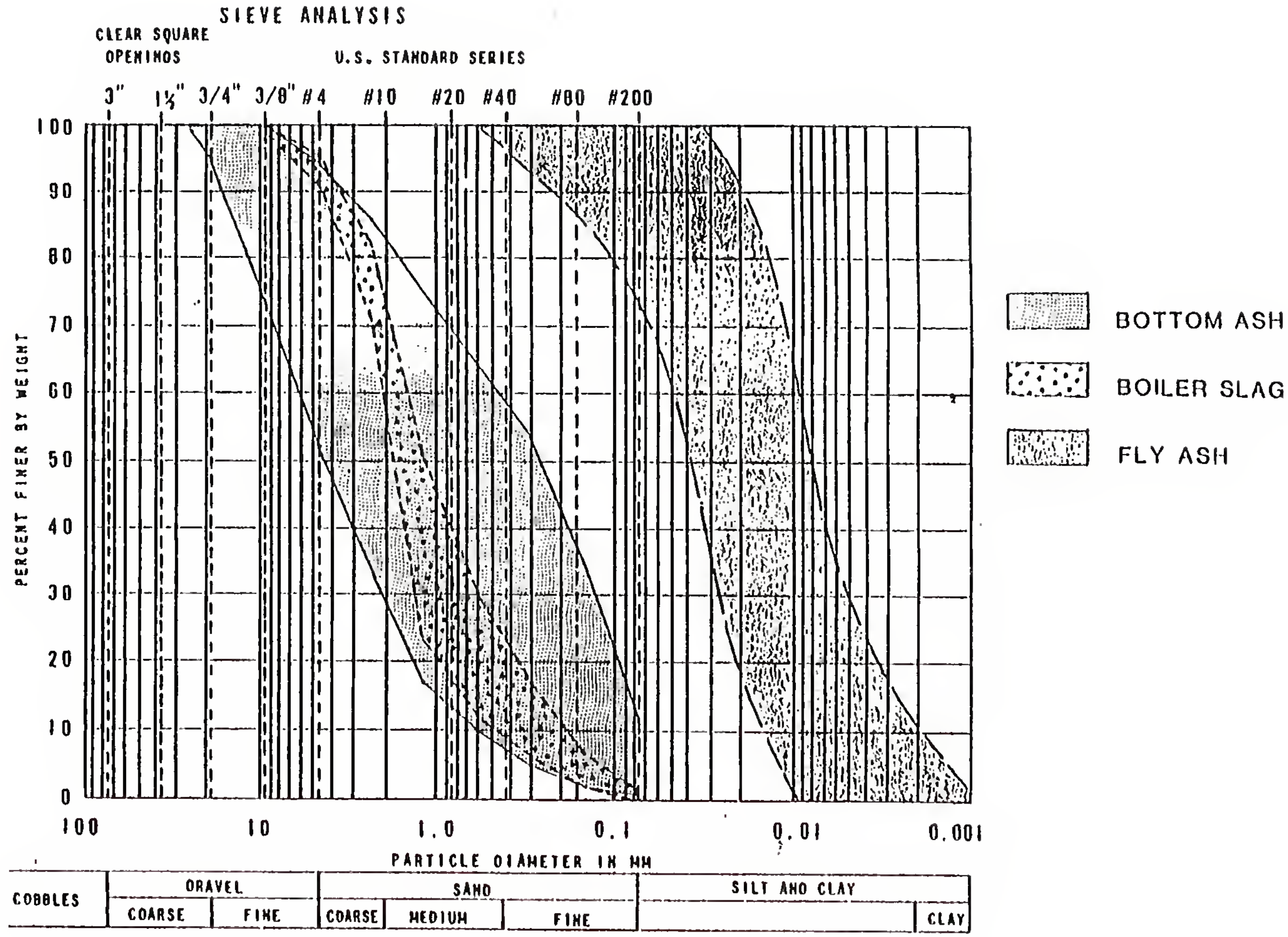


Figure 2.3 Typical Particle Size Distribution Ranges for Coal Ash.
(McLaren and Digioia 1987), (Huang 1990), (USIFCA and GAI 1993).

2.3.2 Mechanical Characteristics

2.3.2.1 Soundness

The soundness of a material provides a measure to the material's resistance to disintegrate because of environmental effects. Cycles of freezing and thawing, wetting and drying, heating and cooling can lead to the weathering of a material. The action of aggressive water can also lead to weathering. The particles of fly ash are too small to be affected by freezing and thawing. The action of the expansive forces from freezing water in pores can be simulated in the laboratory. Bottom ash or boiler slag aggregates of known size can be immersed in sodium sulphate or magnesium sulphate solutions. The particles are then dried in an oven and then re-immersed in the sulphate solution (ASTM C 88-83). The salt precipitates in the permeable pore spaces upon drying in the oven. The rehydration of the salt upon re-immersion in the sulphate solution induces internal expansive forces that can fracture the particles.

The loss in weight of the aggregates retained originally on a certain sieve size indicates a measure of the soundness. The weight loss of bottom ash by this procedure was reported as ranging between 2- 30% (Huang 1990). The range for boiler slag was higher. Thermal stresses due to sudden cooling can lead to the formation of internal fracture planes. Smaller ash particles may contain less fracture planes than the larger ones. Boiler slag grains are affected more by the phenomenon of thermal fracturing than bottom ash. Moreover, bottom ash particles contain larger pores than boiler slag particles, which facilitates the drainage of the sulphate solution before it crystallizes in the oven. Therefore, this test alone may not best discriminate for bottom ash quality. More information is needed to judge on bottom ash soundness. Ke (1990) investigated the durability of Indiana bottom ashes using the Sodium Sulfate Soundness test. Table 2.6 displays the weighted losses based on ASTM C 8-83. The fragile popcorn-like bottom ash particles from Perry had undergone exceptionally high weight losses of 8.12%. The loss range for the typical bottom ashes from Schahfer and Gibson had a range between 2.84 and 1.25%. Freeze and thaw tests following AASHTO T-103 were also conducted on 4 bottom ashes (Ke 1990). The weighted loss after 50 cycles of freezing and thawing in totally immersed conditions are also displayed on Table 2.6. The popcorn-like particles

from Perry were highest in weighted loss. Bottom ashes from Schahfer and Gibson were nearly similar in weighted loss.

2.3.2.2 Hardness and Toughness

Hardness is a measure of the material resistance to abrasion and toughness is a measure of the material resistance to fracture under impact. The measurement of coarse aggregate resistance to degradation by abrasion and impact using the Los Angeles machine is standardized (ASTM C 535-81). Aggregates of known size are placed with steel balls in a rotating steel drum. The drum contains an inner shelf that raises the steel balls and the aggregates then drops them repeatedly as the drum rotates. At the end of the test the aggregates are sieved and weighed to measure the degradation due to abrasion and impact as percent loss. The percent weight loss of the initial sizes ranged between 27 and 53% for bottom ash and between 24 and 47% for boiler slag. Bottom ash particles degradation by this test was found to be mainly due to particle fracturing rather than surface wearing by abrasion (Huang 1990). Due to the porous nature of the bottom ash particles they are affected by this test more than the boiler slag particles. The percent loss also increases as the aggregate size increases, since coarser aggregates are more porous. This test provides indication of the possibility of particle crushing under the compaction equipment. The less the weight loss is, the better the quality of the ash.

2.3.2.3 Compaction

a- Compaction of Coal Ash

Compaction has long been recognized as an effective technique to stabilize soils. Compaction is normally applied to bring the soil particles to a denser and more stable arrangement. Accordingly, the shear strength of the soil is increased and the soil compressibility and permeability are decreased. This is normally achieved by the expulsion of air from the soil system and rearrangement of the solid particles, using vibration, impact, kneading, or pressure. Soil has long been compacted in highway

Table 2.6 Results of Soundness and Freeze-Thaw Tests on Bottom Ash (Ke 1990)

Ash Source	Soundness Tests[a] Weighted Loss[c] (%)	Freeze-Thaw Tests[b] Weighted Loss[d] (%)
Perry K	8.12	7.66
Gibson	2.84	3.38
Schahfer		
Unit 14	1.25	2.26
Unit 17	2.53	3.55

[a] Following ASTM C 88 or AASHTO T 104.
[b] Following AASHTO T 103.
[c] After 5 cycles of immersion and oven-drying.
[d] After 50 cycles of freezing and and thawing in a totally immersed condition.

embankments using different types of rollers, with or without vibrations. Normally the fill is placed in loose lifts at a certain moisture content, then passed on by a suitable roller as many times as required for the achievement of a certain minimum density. The compaction level can be typically specified in terms of the relative compaction R%, where,

$$R = \gamma_d / \gamma_{dmax} \tag{2.1}$$

γ_d = dry unit weight

γ_{dmax}= maximum dry unit weight based on a standard laboratory method (e.g. ASTM D 698-91).

The compaction of natural soils have been studied extensively in the past (e.g., Proctor 1933; Lambe 1958; Joslin 1959; Foster 1962; Hodek and Lovell 1980; Hilf 1991). Fly ash, follows similar trends in compaction to those of low plasticity cohesive soils. Dry ash can be very difficult to compact. The addition of moisture to dry ash can generally assist the compaction procedure. An increasing moisture content during compaction leads to an increasing dry unit weight until a maximum unit weight is reached at a moisture content called the optimum moisture content. If more water is added, beyond the optimum, the soil dry unit weight drops. Moisture contents less than the optimum moisture content are called dry of optimum. Moisture contents greater than the optimum moisture content are called wet of optimum. The relationship between the compaction moisture content and the compacted dry unit weight of a cohesive soil is displayed in Figure 2.4. Increases in the compaction energy reduce the required moisture for obtaining the same dry unit weight. Conformal curves that have an apex at lower moisture contents result from higher compaction energies. Figure 2.5 display typical compaction curves for bituminous fly ashes. Figure 2.6 display the compaction curves of subbituminous and lignite fly ashes.

Although the microstructure and hydration mechanisms of a cohesive soil are totally different from that of a fly ash, the shapes of the compaction moisture-density curves are relatively similar. The compaction moisture significantly affects the compacted clay fabric. Class F fly ash particles are non-plastic. The effects of water during the compaction of a fly ash are more related to lubrication than hydration. Moisture

facilitates handling of the fly ash. Dry fly ash is difficult to handle. It can easily be disturbed, causing dusting. Conditioning the fly ash is an essential step before compaction. The compacted dry unit weight of the fly ash is sensitive to small changes in the compaction moisture contents. In other words, the compacted dry unit weight may change rapidly over a narrow range of moisture. The compacted unit weights are typically smaller than those of most soils.

The bottom ash response in compaction is mostly similar to that of cohesionless soils. Cohesionless soils display a different behavior in compaction from that of cohesive soils. If a dry cohesionless soil is compacted using a certain compaction energy, it will reach a certain dry unit weight. Unlike what is observed for cohesive soils, the gradual addition of water leads initially to reduction in the compacted dry unit weight of cohesionless soils (Foster, 1962). As more water is added, the unit weight starts to increase gradually with increasing the water content until all the voids are saturated with water (Figure 2.7). If more water is added after the saturation point, the dry unit weight will gradually decrease again. The reduction of dry unit weight at low moisture contents is called "bulking". Capillary tension develops, leading to the development of an apparent cohesion between the particles. The apparent cohesion resists the rearrangement of the particles during compaction. Increasing the water content gradually reduces capillary tension. Thus, the bulking vanishes and the soil reaches the maximum response to compaction and highest unit weight is achieved. Consequently, no further increase in dry unit weight is achieved by increasing the moisture content. Compaction of bottom ash and boiler slag tends to follow the trends experienced in compacting cohesionless soils. Nevertheless, due to the complex pore structure of bottom ash aggregates, irregular response to compaction may be produced (Huang 1990). Figures 2.8 display the compaction curve for a bottom ash from Gibson power plant. The bulking effects on the dry unit weights obtained at low moisture content range can be easily noticed. Flushing bottom ash in the field just before compaction was considered as an effective solution to avoid bulking (Huang 1990). However, special considerations have to be applied if a clay liner system exist below the bottom ash fill.

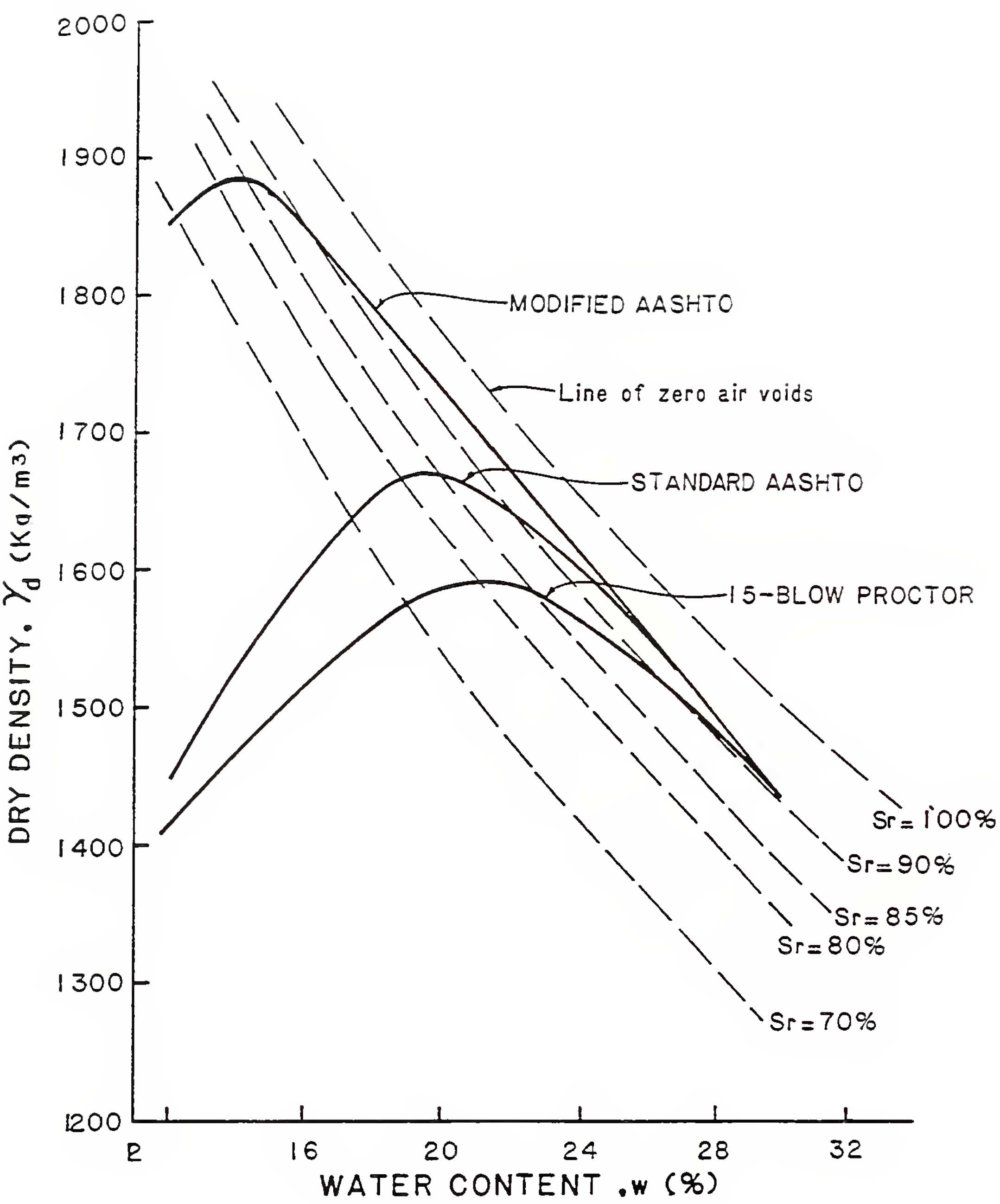


Figure 2.4 Typical Moisture-density Curves for A Compacted Cohesive Soil. (Nwabouki 1984)

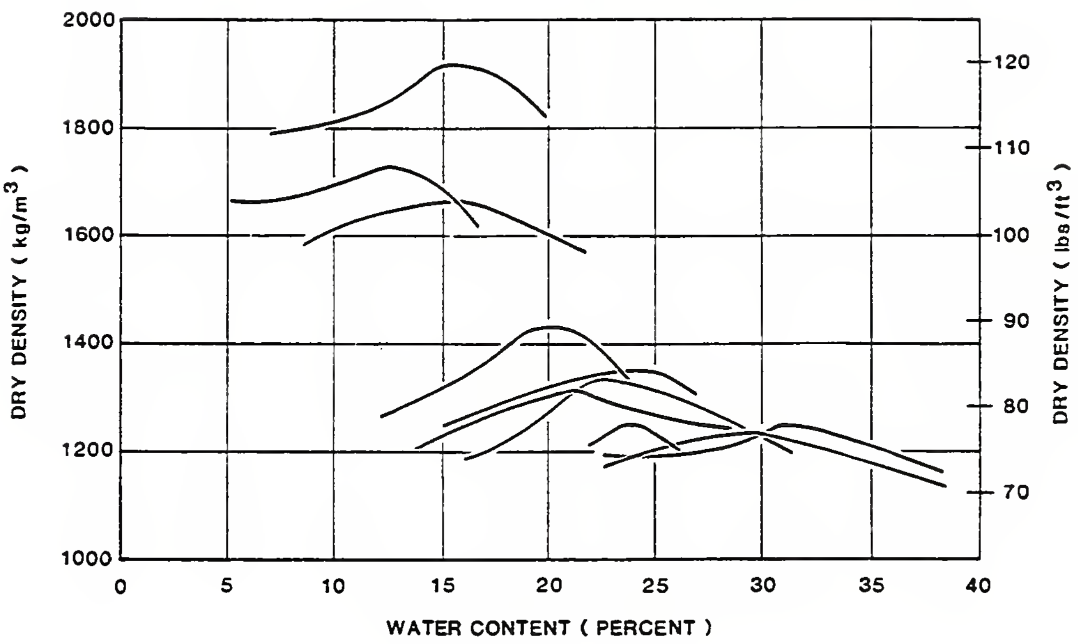


Figure 2.5 Typical Compaction Curves for Western Pennsylvania Bituminous Fly Ashes. (DiGioia et al. 1986)

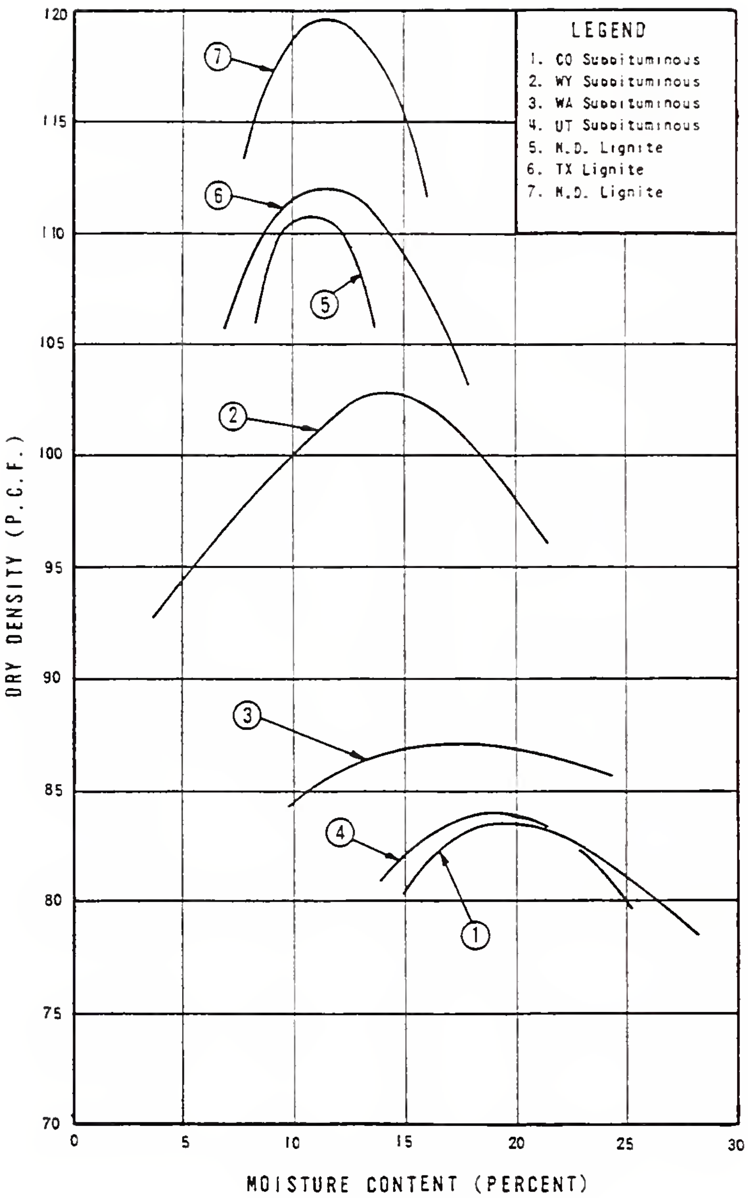


Figure 2.6 Typical Compaction Curves for Western United States Lignite and Subbituminous Fly Ash. (DiGioia et al. 1986)

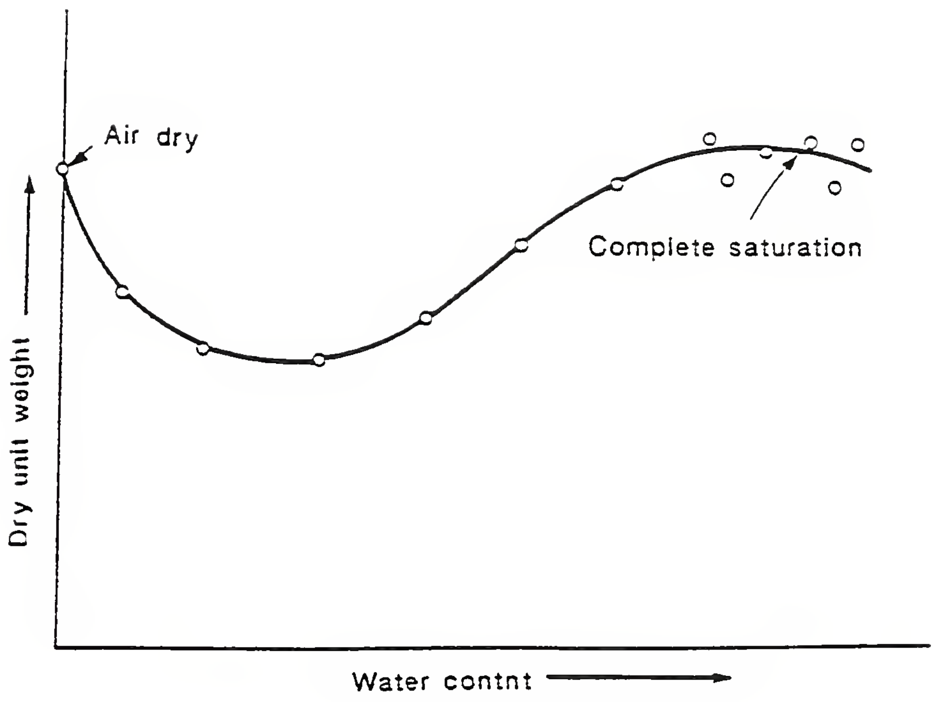


Figure 2.7 Typical Moisture-density Relationship for Cohesionless Soils. (Foster 1962)

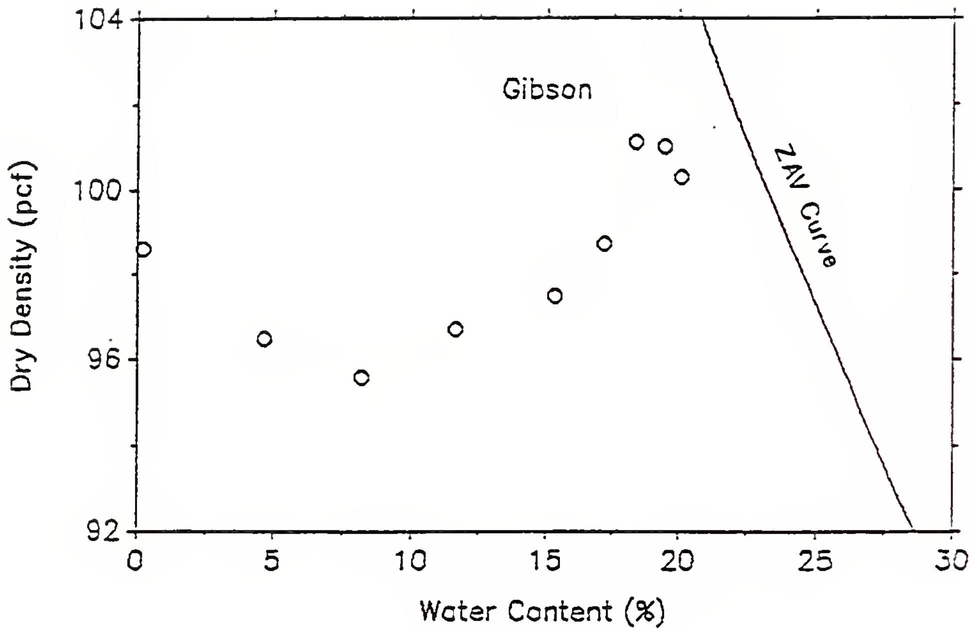


Figure 2.8 Moisture-density Curve for Bottom Ash from Gibson Power Plant, Indiana. (Huang 1990)

b- Control of Field Compaction

The control of the compaction procedures in the field is necessary for achieving a targeted level of performance from a compacted fill. One of three methods may be adopted for writing the compaction specifications (Lovell 1991): a) End Results, b) Procedure Specification, and c) A Combination of (a) and (b). Method (a) specifies the minimum unit weight that may be achieved from the field compaction in terms of a percentage of a standard laboratory maximum unit weight using a standardized compaction effort. It also specifies a range of moisture contents to be used for achieving the targeted unit weight from the compaction. Method (b) includes a detailed specification of the field compaction process. The loose lift thickness, the compactor type and weight, the number of passes, the vibration frequency, and the rating of compaction may be specified. Method (c) would include both the compaction details and the end results. This third method provides more control over the compaction process; nevertheless, for successful compaction, it requires more experience on behalf of the specification writer.

Many test methods have been developed to assist the compaction quality control in the field. Detailed discussions of these methods and their limitations were reported by Johnson and Sallberg (1960), Holtz and Kovacs (1981), and DiGioia et al. (1986). The control of compaction in the field is typically achieved by testing the compacted fill for dry unit weight and moisture determination. The simplest methods for the determination of the unit weight in the field involve sample extraction. Yet, these methods are, somewhat, time consuming. The most popular methods in this category are the sand cone method (ASTM D 1556-90), the rubber balloon method (ASTM D 2167-84), and the oil (or water) replacement method (ASTM D 5030) (Figure, 2.9). In these methods, a volume of soil is removed for moist weight determination, and replaced by a measurable volume of another material. These methods have long been and still are utilized for the control of compaction. However, due to concerns about the time consumed in drying the retrieved soil in conventional ovens, techniques for soil drying, such as pan frying and microwave oven are utilized.

Another method that utilizes chemical reactions for water content determination is the Speedy method. It uses reactions of carbide with the water content to produce

acetylene gas. The gas pressure, which is proportional to the moisture content, is measured on a calibrated gauge and correlated to the moisture content. Correlations between this indirect method and the conventional oven is usually necessary for obtaining good results (Holtz and Kovacs 1981).

The nuclear density gauge, is another quick method that is used almost routinely at the present time in moderate and large size projects. It involves emitting a small dose of gamma rays that penetrate the compacted lift and become scattered due to collision with the soil particles. The amount of scatter is correlated to the total unit weight of the material. The collision of neutrons with the hydrogen atoms in the water leads to their scatter and provide means to determine the water content (ASTM D 3017-88; Holtz and Kovacs 1981). One limitation of this method is that the chemical composition of the sample may drastically affect the measurements. There is no universal correlation that fits all soils. Each type of soil or fill has to have a material specific correlation for direct unit weight determination. Unless reliable calibration and correlations are performed for the nuclear density gauge, some difficulty with the accuracy of the method can be experienced in practice. Sand cone with conventional oven drying is usually used as a reference method for calibration and correlation.

A new method using the technique of time domain reflectometry (TDR) was recently developed (Siddiqui and Drnevich 1995) for measuring the in-place density and moisture content of soils. The method can be used for the field as well as the laboratory. In the laboratory, the soil is compacted in a cylindrical metal mold with a base made of a nonconductive material (wood or delrin). A coaxial transmission line is inserted in the soil and the dielectric constant is measured. As the weight of soil in the mold is measured and the total unit weight defined, the moisture content of the soil is determined by the use of a known relationship.

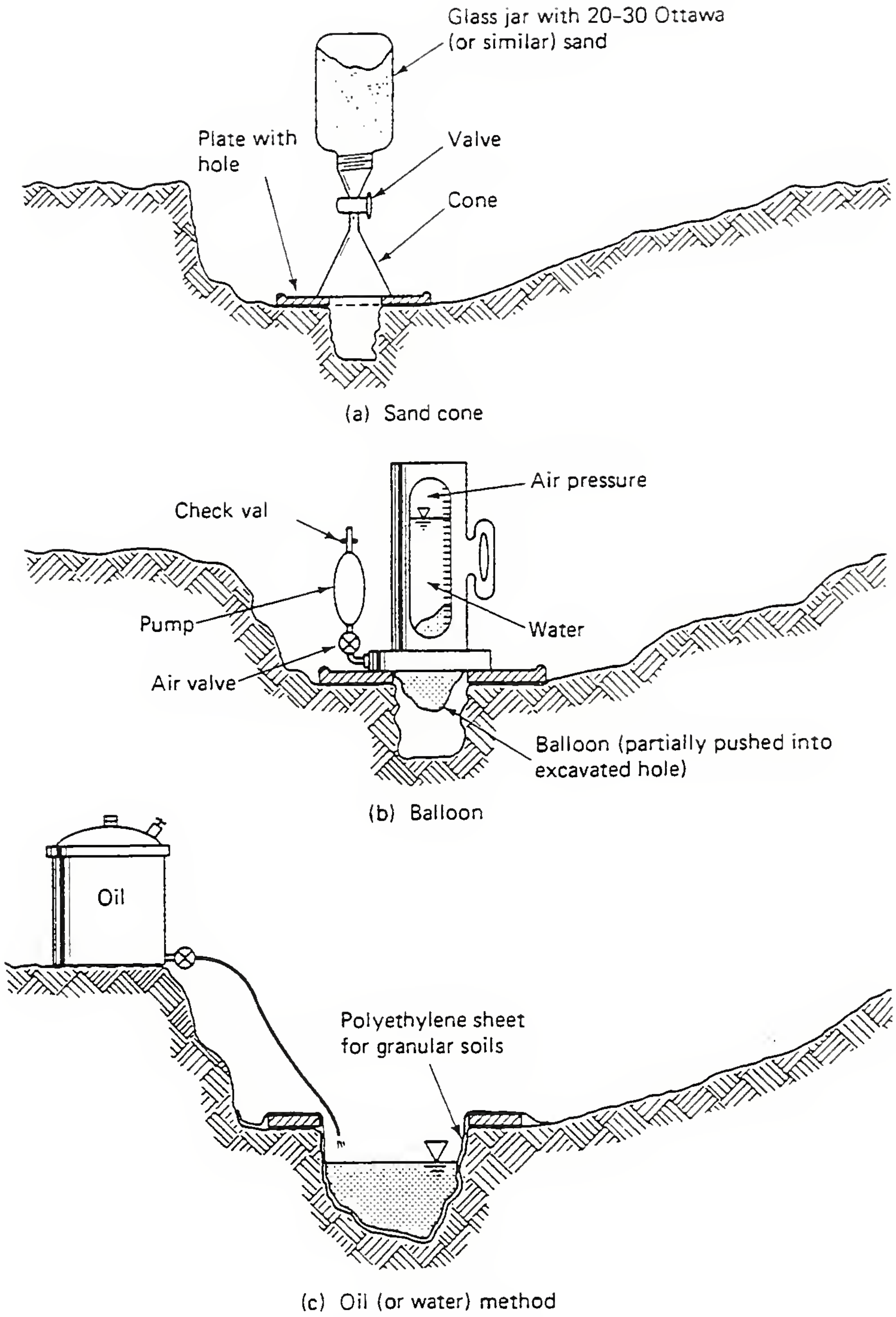


Figure 2.9 Field Methods for Determining the Soil Unit Weight . (Holtz and Kovacs 1981)

The dry unit weight and compaction moisture contents are not objectives themselves but rather indications of a performance level to be expected. For example, Lin and Lovell (1983) reported that the compaction moisture content affects the amount and direction (expansion or compression) of deformation of a compacted cohesive soil upon wetting. Compaction dry of optimum leads to more expansion upon saturation at small loads and larger compressions at large loads. Compaction wet of optimum reduces or eliminates the swelling potential at small loads and leads to larger compressibility at small and intermediate loads. The shear strength of soils compacted wet of optimum tend to be less than that of soils compacted dry of optimum. The study of the behavior of compacted ash mixtures can provide information about how the shear strength changes due to changes in compaction water content. This can provide guidelines on how stringent the specifications of compaction should be in terms of water content ranges.

One of the methods that are often used in estimating the objective water content and dry densities in the field is the one-point method. The method was originally adopted for use in Ohio and Wyoming (Johnson and Sallberg 1960). A group of typical compaction moisture-unit weight curves were developed. Performing only one compaction test on a soil and plotting the result on the group of curves allow the prediction of the maximum unit weight and the optimum moisture. The method assumes that soils having the same maximum unit weight have similar moisture-unit weight curves. The method further assumes that curves for higher weight materials have their maximum unit weight occurring at lower optimum moisture contents and that the slope of the compaction curves are relatively similar. The accuracy of the method can be enhanced as the "one point" is located near the optimum. It was reported that the method was used successfully in the past in determining the targeted density for field compaction of a Class F fly ash (Srivastava and Collins 1989).

2.3.2.4 Hydraulic Conductivity

The hydraulic conductivity of a soil expresses the ability of a fluid, mostly water in this context, to be conducted through its interconnected voids system. The hydraulic conductivity is influenced by the solid void system in general. It is affected by the

connectivity, the number, the sizes, the tortuosity of voids in soil. Those are commonly related to the particle sizes, the gradation, the relative unit weight, and the particle shapes and texture. The hydraulic conductivity of compacted bottom ash ranges from 1 x 10^{-1} cm/sec to 5 x 10^{-3} cm/sec (Huang 1990). The hydraulic conductivity of compacted fly ash is significantly lower than the bottom ash. For compacted fly ash normal range is between 1 x 10^{-4} cm/sec to 1 x 10^{-6} cm/sec (GAI and USIFCAU 1993). Wayne et al. (1991) conducted a series of hydraulic conductivity tests on Class F fly ash. They concluded that a hydraulic conductivity of 3.2 x 10^{-5} cm/sec could be reached for samples compacted at 90% of standard Proctor effort. This range is similar to the range of hydraulic conductivity of silts reported by Das (1985).

2.3.2.5 Compressibility

The compressibility of a material indicates its behavior in deformation under static vertical loads. Due to their low hydraulic conductivity, saturated cohesive soils tend to take a long time to reach final deformations under vertical loads. Granular free draining materials deform almost instantly under loads. Bottom ash with low fines content can be considered as a free draining material. In this case settlements are instantaneous. Fly ash is less permeable than bottom ash, but, it is more permeable than compacted cohesive soils. Accordingly, settlements are likely to take place fully during construction.

At relatively low and intermediate stress levels, initial deformations of bottom ash may involve particle reorientation and distortion. Compressibility of bottom ash and boiler slag at intermediate stress levels may be comparable to compressibility of granular materials of similar gradations and relative densities at similar stress levels (Huang 1990; Seals et al. 1972). Seals et al. (1972) reported the results of testing bottom ash samples in one dimensional compression at two levels of relative Density. The responses of bottom ash in both loose and dense states are displayed (Figure 2.10). At high stress levels, particle crushing increases and can have pronounced effects on the compressibility behavior of the ash. The critical level of particle crushing depends upon the particle size, angularity, strength of individual particles, and the grain size distribution (Lambe and Whitman 1979). Huang (1990) reported similar trends for the compressibility of

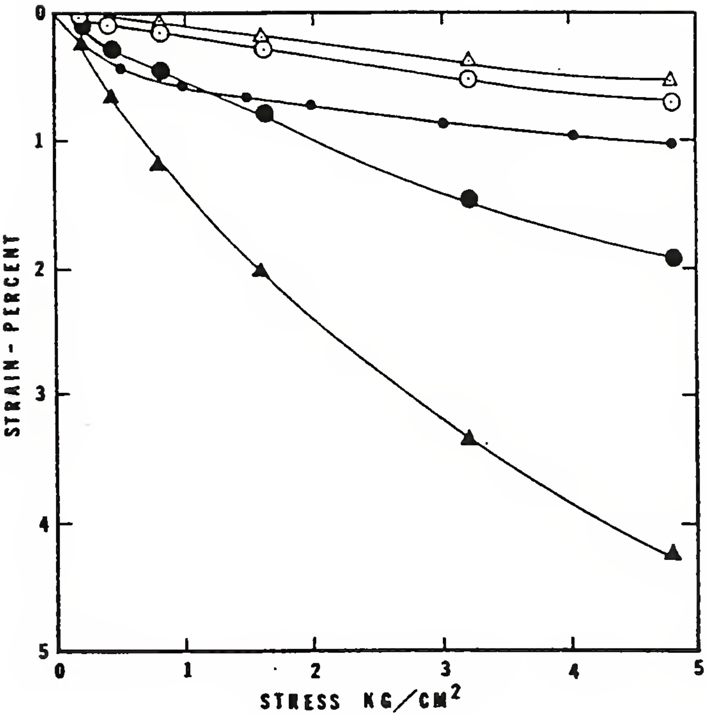
bottom ashes from Indiana power plants. Figure 2.11 displays the results of one dimensional compression tests on bottom ashes and a medium sand. Figure 2.12 Displays the constrained modulus versus the vertical stresses. Particle crushing is responsible for the observed lower values of constrained modulus for bottom ash compared to those of the medium sand.

The behavior of Class F fly ash in compressibility is comparable in general to that of cohesive soils. However, since the hydraulic conductivity of the compacted fly ash is greater than that of a compacted plastic soil, fly ash is hence expected to deform in considerably higher rates than cohesive soils. McLaren and DiGioia (1987) reported values of the compression index of fly ash, C_c. The average value presented for C_c is equal to 0.13, with a standard deviation of 0.088 and a coefficient of variation of 67.1%. Figure 2.13 displays the stress versus the void ratio of a stockpiled fly ash (Srivastava and Collins 1989). Fly ash can undergo large deformations if it is not well compacted.

The compressibility behavior of ash mixtures is more complex than that of a single ash type. It depends upon the fine ash content in the mixture, the state of compaction, the load level and the strength of the aggregates. Very little information is published on ash mixture compressibility. However, most of the settlements are expected to be completed during the construction period.

2.3.2.6 Shear Strength

The evaluation of the shear strength of compacted ash is essential for the appropriate design of embankments. Bottom ash and boiler slag are basically cohesionless materials. Dry fly ash is a powder-like material. As it becomes wet, it develops apparent cohesion as a result of capillary tension. This type of cohesion vanishes upon saturation. Class F fly ash requires the addition of lime and water to produce permanent cementing. The shear strength of soils is typically expressed in terms of the effective strength parameters c', ϕ'; where, ϕ' is the effective angle of shearing resistance and c' is the



SOURCE	VOID RATIO	RELATIVE DENSITY
KAMMER	⊙ 0.62	78.9
	● 0.81	29.1
MITCHELL	△ 0.64	64.2
	▲ 0.84	16.7
MEDIUM SAND UNIFORM	• 0.65	

Figure 2.10 One-dimensional Compression of Bottom Ash and Sand. (Seals et al. 1972)

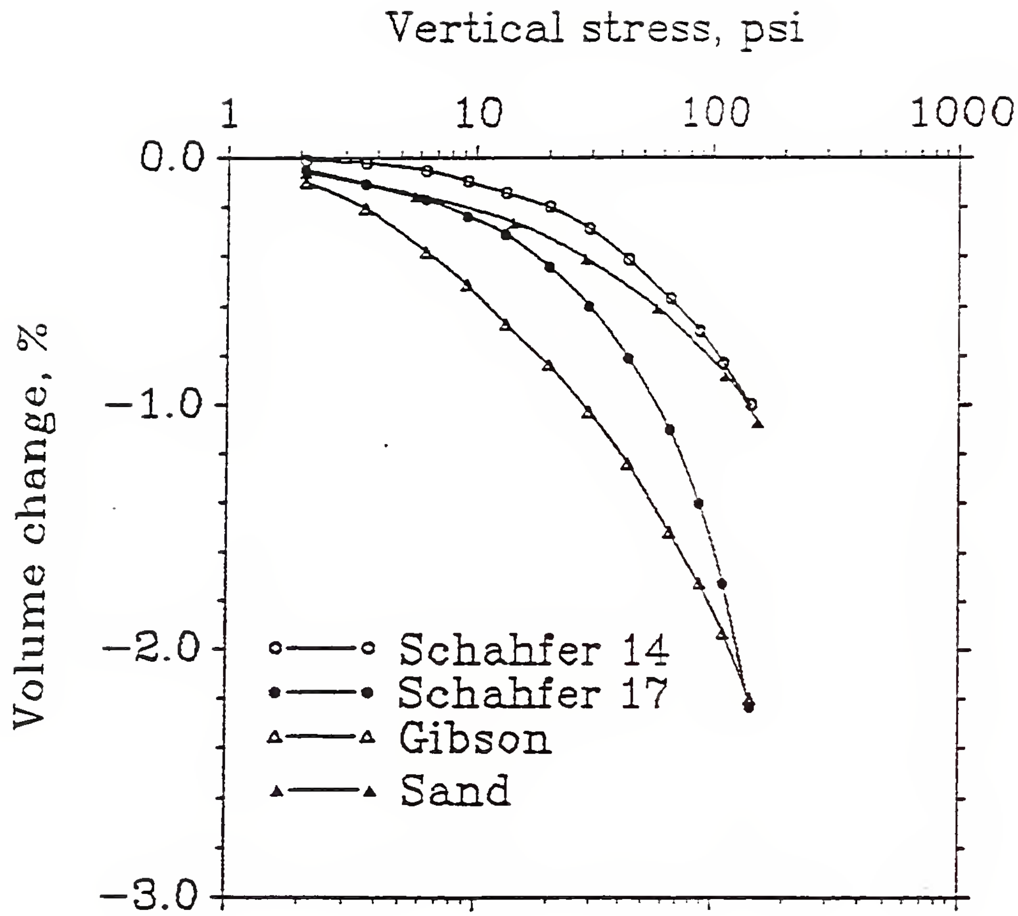


Figure 2.11 One-dimensional Compression of Indiana Bottom Ashes and a Medium Sand. (Huang 1990)

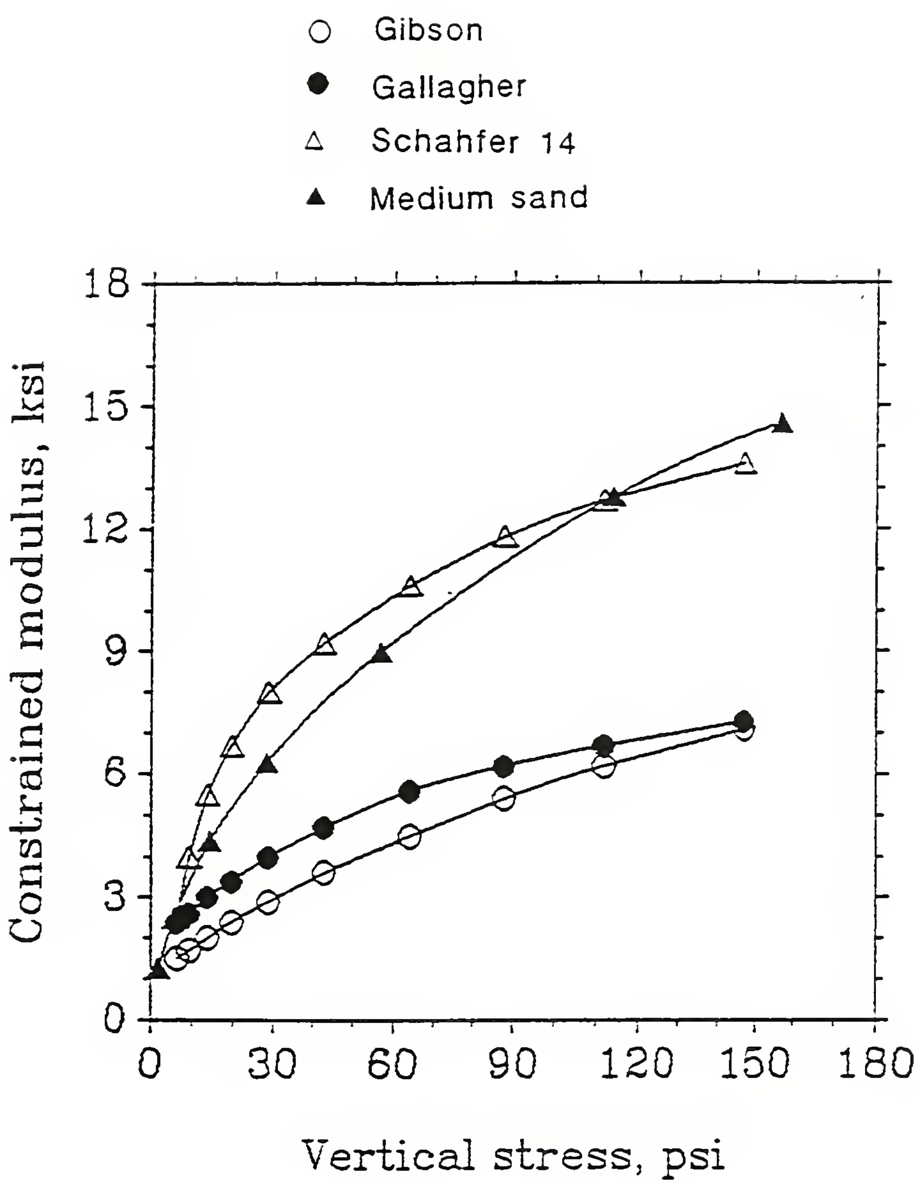


Figure 2.12 Constrained Modulus Vs. Vertical Stress Curves for Indiana Bottom Ashes and a Medium Sand. (Huang 1990)

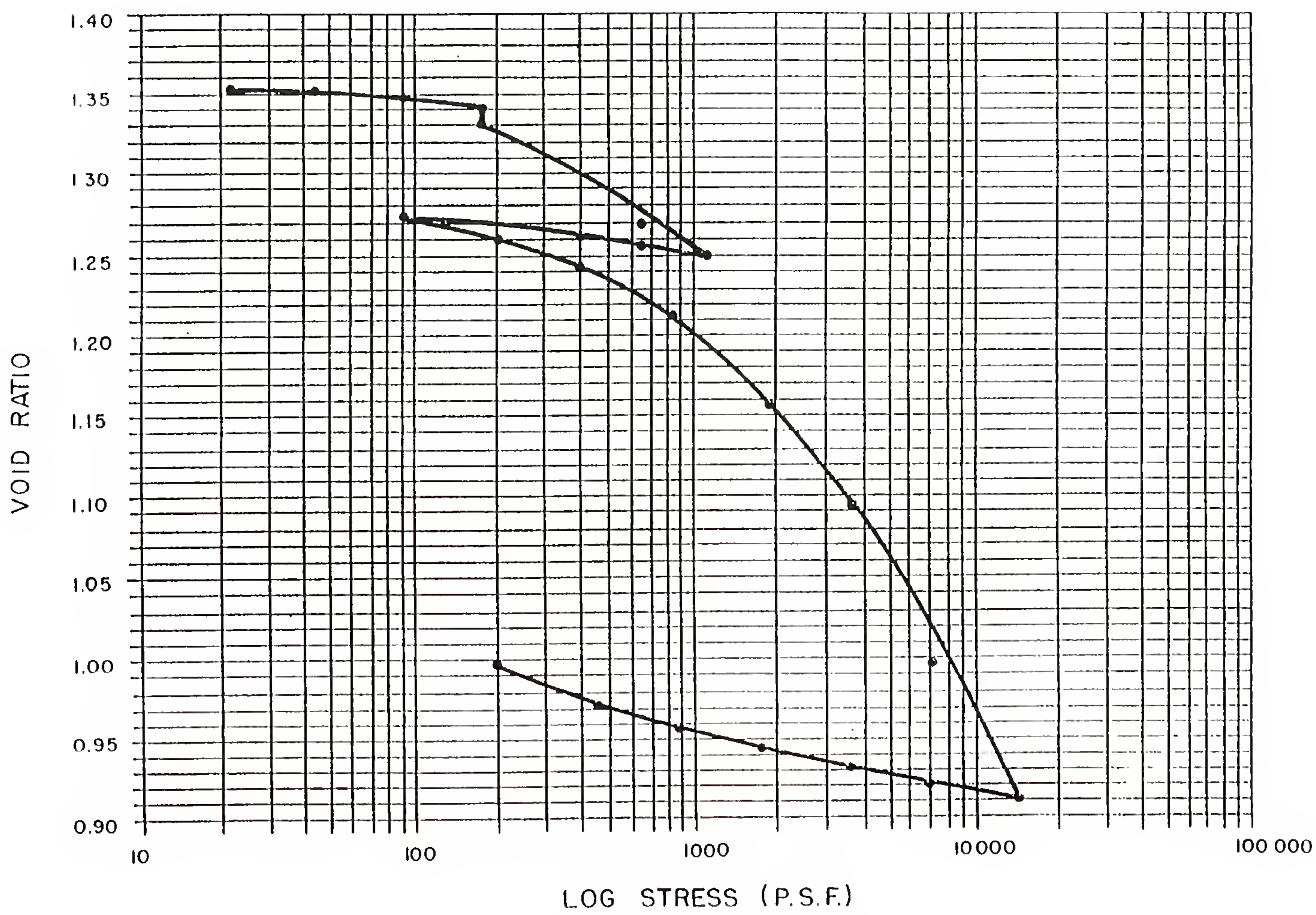


Figure 2.13 Consolidation Test Data on Delmarva Stockpiled Class F Fly Ash Utilized in the Delaware Demonstration Project. (Srivastava and Collins 1989)

effective cohesion. The evaluation of the shearing strength parameters is important for the assessment of the stability of slopes, the bearing capacity of foundations, and the lateral pressure of backfill against retaining structures.

The mechanisms that contribute to granular soil deformations are the distortion and crushing of individual particles, and the relative movements between the individual particles due to rolling and sliding at all stress levels. Failure of granular soils occur due to the formation of a sliding surface where particles start moving over one another. Resistance to failure is developed due to surface friction and particle interlocking. Particle crushing can occur at different stress levels. It was reported (Lambe and Whitman 1979) that particle crushing starts at small stresses, however their effects become more significant when some critical stress is reached. This stress is low for the large, angular, and weak particles. Loose uniform soils usually reach crushing faster than dense well graded soils of the same mineral composition. For well graded quartz, it was reported that a good fit for Mohr's failure envelope as a straight line may be obtained at stresses up to 1000 kPa (172 psi). For calcareous sand, a good fit may only be obtained for stresses up to 500 kPa (71 psi). The reason for lower values in the case of calcareous sand is the occurrence of considerable particle crushing that results in the reduction of the angle of shearing resistance. This leads to a curvature of the failure envelope (Lambe and Whitman 1979).

An analogy may be drawn between the behavior of natural soils and the behavior of coal ash in shear strength. Bottom ash and boiler slag can be investigated in view of granular cohesionless soils. In general, the shearing resistance of a cohesionless soil is affected by the relative unit weight, the void ratio, the confining stresses, the sample size, the test type, and the rate of strain. It is also affected by the grain size distribution, the strength of the individual particles, the size, the shape, and the surface texture of soil particles as well (Lambe and Whitman 1979; Rodriguez et al. 1988). Since denser packing can be more easily achieved in well graded, rather than uniformly graded soils, ϕ' is higher for well graded soils. A generally similar behavior was reported for bottom ash and boiler slag (Huang 1990).

The addition of small percentage of fines (fly ash) leads to increasing dry unit weight and the strength in terms of CBR test results. However, the maximum strength was achieved at fines content lower than that for maximum unit weight. Hard granular particles do not crush at low stresses, the angle of shearing resistance does not decrease until reaching relatively high stresses. Bottom ash particles may be more fragile than natural sands, hence ϕ' may start decreasing at lower stresses. Angularity of particles provide more interlocking, and hence greater ϕ' for angular particles than rounded. Bottom ash and boiler slag particles are generally angular to subangular. Nevertheless, angularity increases the amount of crushing at low stress levels, because high stress concentrations can take place.

Large particles need more effort to overcome the interlocking than small particles in natural sands. This indicates greater shear strength for sands that contain larger size particles. However, this must be viewed carefully when investigating bottom ash and boiler slag because larger particles of bottom ash are more porous and may undergo particle crushing at lower confining stresses than the smaller particles. Table 2.7 displays the angle of shearing resistance, obtained by direct shear tests, for samples of bottom ash, boiler slag, and sand (Seals et al. 1972; Lambe and Whitman 1979; Sowers and Sowers 1951). The angle of shearing resistance for bottom ash typically ranged from 32° to 44° and for boiler slag from 37° to 46° (GAI and USIFCAU 1993; McLaren and DiGioia 1987). Huang (1990) reported a slightly wider range of ϕ' also from direct shear tests (Table 2.8). Srivastava and Collins (1989) reported a value for ϕ' of 34.5° from triaxial tests on pulverized bottom ash. The value of ϕ' for pulverized bottom ash was greater than that for natural sands of the same size (Figure 2.14).

The angle of shearing resistance for compacted Class F fly ash was reported to have a range from 25° to 40° (GAI and USIFCAU 1993). McLaren and DiGioia (1987) reported an average value for Class F fly ash of 34° with standard deviation of 3.3° and coefficient of variation 9.8%. In a comparison between shear strengths of sand and fly ash, Parylak (1992) reported the tendency of having more curvature in Mohr's envelopes for fly ash than for sand. The fly ash utilized in that study contained more than 85% by

Table 2.7 Results of Direct Shear Tests on Loose Bottom Ashes (Seals et al. 1972)

Ash Source	Boiler Type	Average Void Ratio	Angle of Internal Friction (Degree)
Fort Martin (Unit 2)[a]	Dry Bottom	1.41	40.0
Kammer[a]	Wet Bottom	0.88	41.0
Kanawha River[a]	Dry Bottom	1.68	38.0
Mitchell[a]	Dry Bottom	1.08	42.5
Muskingham[a]	Wet Bottom	1.33	40.0
Willow Island[a]	Wet Bottom	1.32	42.0
Ottawa Sand[b]	-	0.54-0.66	29-35
River Sand[b]	-	0.61-0.79	33-41
Angular, Uniform[c]	-	-	35-43
Angular Well Graded[c]	-	-	39-45

[a] Tests performed on minus 3/4 in. material.
[b] Data from Lambe and Whitman (1979).
[c] Data from Sowers and Sowers (1951).

Table 2.8 Results of Direct Shear Tests on Selected Indiana Bottom Ashes (Huang 1990)

Material Source	Loose Strength Intercept (psi)	Loose Values of ϕ' (deg)	Dense Strength Intercept (psi)	Dense Values of ϕ' (deg)
Schahfer				
Unit 14[a]	0.48	35.1	1.49	46.3
Unit 17	0.14	39.2	3.12	47.7
Gibson	0.20	44.8	1.66	55.0
Gallagher	0.49	41.3	2.00	51.6
Perry	0.49	41.5	3.00	50.6

[a] Boiler slag (wet bottom ash)

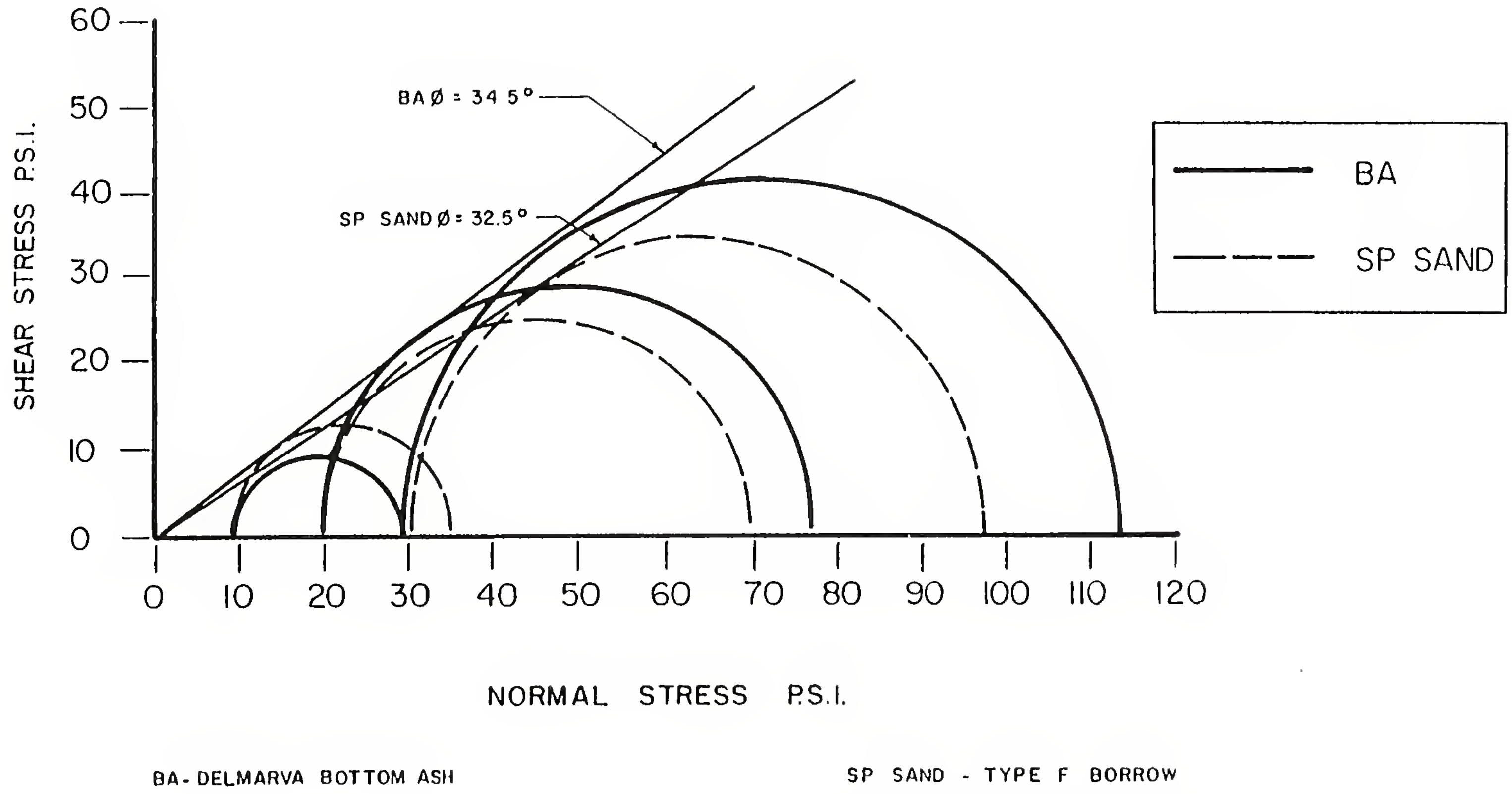


Figure 2.14 Triaxial Test Results for Pulverized Bottom Ash Samples. (Srivastava and Collins 1989)

weight in the sand size, which is not common for fly ashes. Wayne et al. (1991) tested Class F fly ash to evaluate its utilization as a structural fill in a highway embankment. The triaxial tests were conducted to investigate the ash behavior in shearing. One of their main concerns was the strength for long term conditions. They used consolidated-drained triaxial tests on saturated samples to simulate this behavior under saturated conditions. They also performed slow drained tests on as compacted partially saturated samples. The idea was to investigate the long term response of the unsaturated fill. The strain rate was adjusted (0.0001 in/min.) to ensure a drained response for theses samples, but no suction measurements were made.

A comparison between the triaxial tests and shear box tests for testing coal ash was recently reported by Clarke et al. (1993). They recommend the use of triaxial tests since they are more controllable. The saturation process in the shear box tests may remain partial and the results may be affected by the suction. In the triaxial tests, drainage is controllable and the failure surface is not predetermined (Bishop and Henkel 1962). On the other hand, triaxial tests are more time consuming and have limitations also that need to be considered.

2.4 Coal Ash Utilization In Embankment Construction

The construction of highway embankments requires substantial amounts of fill materials. Soils, being the common source for such fill, are usually transported from nearby borrow areas. Coal ash can be viewed as one of the viable alternatives for soils. It can offer several advantages over many soils and rocks. Coal ash has a lower unit weight than most soils. This property can be useful, especially when the compressibility of the foundations is a source of concern. Relatively high shear strength can be obtained if the coal ash is compacted appropriately. High shear strength allows for steeper slopes and higher embankments. The ease of moisture control, especially in the case of dry fly ash, simplifies the quality control of the compaction and encourages the utilization of coal ash in construction. The availability of the coal ash, in locations where natural soil sources may be scarce, makes their utilization beneficial in places such as the highly developed urban areas. If costs of coal ash are kept low, compared to most natural soils,

the feasibility of using coal ash is enhanced. It also encourages the interested parties (industry, governmental agencies, consultants, universities) to investigate thoroughly this alternative.

There are, however, some limitations associated with the use of coal ash. These limitations can be addressed by appropriate measures and precautions. The limitations are mainly because of economic related concerns, mechanical performance concerns, and environment related concerns. The economic concerns include costs due to special design and construction considerations, and the additional training required for the design and construction teams. The costs associated with the additional training required for the construction and quality control teams are actually reduced every time a new project is finished. The costs of the special design and construction considerations can be covered if the costs of coal ash remain at low levels.

The performance concerns are related to the mechanical behavior of the coal ash. Single types of ash were utilized successfully in several demonstration projects. Examples of these projects are presented later in this section. Utilization of coal ash mixtures is still restricted due to uncertainties associated with their mechanical performance and the control of their compaction. The topic of this study is the investigation of the compaction and shear strength of compacted mixtures of coal ash. Detailed examination and discussions of these behaviors are included in the successive chapters.

The utilization of coal ash can lead to conserving natural soils near urban areas and reduce the costs associated with ash disposal. Rather than conserving natural soils, using coal ashes types III and IV (Indiana Administrative Code, 329 IAC 2-9-3)can be environmentally safe. Strict limitations have been placed upon the proportion of trace elements contained in their leachates. The environmental concerns are discussed further in the following section.

2.4.1 Overview of Current Practices of Coal Ash Utilization in Highway Construction

The accumulation of huge amounts of coal ash in landfills and disposal ponds encouraged many agencies to become involved in finding alternatives to coal ash disposal. The characteristics of coal ash differ based upon type. Fly ashes are very fine

materials that have light unit weight. Class F fly ash has pozzolanic properties that need the addition of lime and water to start cementing reactions. It is generated in large quantities and can be successfully used as fill. Class C fly ash has self cementitious properties that allow its use as an additive in cement mixtures or as a cement substitute. Bottom ash has stable composition that favors its use as an aggregate substitute or as a fill. Boiler slag currently has a better market than bottom ash. Table 2.9 summarizes the current uses of coal ash in highway construction.

2.4.2 Environmental Concerns for Coal Ash Utilization in Embankments

The utilization of coal ash in embankment construction has increased during the last decade. The main environmental concerns are dusting, erosion, and leaching. Coal ash has been treated as a waste material for a long time. The practices for the coal ash disposal were directed to minimize the disposal cost rather than to improve the quality of the coal ash as a construction material. The nature of the coal, the burning process, and the disposal process all affect the ash composition and its quality and hence the impacts on the environment. All these factors motivated research to investigate these impacts. This is a very active area of research on its own.

2.4.2.1 Dusting

Dusting is generated if dry ash fines are disturbed. The fly ash particles are very small. They mainly fall in a size range similar to silts and coarse clays. The dry fly ash particles have no cohesive forces between themselves, and hence are very easily disturbed forming dust. Many measures are commonly taken for the fly ash handling and utilization in construction to minimize the dusting problems. The dry fly ash is routinely transported using pneumatic tankers similar to those used for transporting bulk portland cement from manufacturer's silos to concrete mixing stations. Special equipments are usually used for the ash placement and moistening. Conditioning the ash using water normally reduces the dusting problem (DiGioia et al. 1986). To store the fly ash in stockpiles, it has to be kept moist (approved anti dusting materials or water may be used) or have some type of stable cover on top of it. The containment of the ash under soil

Table 2.9 Utilizations of Coal Combustion By-Products In Highway Applications (USDOC 1988)

Uses of Fly Ashes

* Raw material in Portland Cement
* Replacement for cement in concrete
* Cement replacement in precast concrete products
* Ingredient in aerated concrete
* Mineral filler in asphaltic concrete
* Stabilization of highway subgrades
* Raw material in the manufacture of lightweight aggregates
* Material for structural fill
* Material for flowable fill or backfill
* Ingredient in grouting
* Stablized fly ash base course without aggregate
* Stablized fly ash-aggregate base course

Uses of Bottom Ash

* Aggregate in ashphalt
* Ingredient in bituminous stablized base for highways
* Aggregate in Portland cement stablized bases for highways
* Snow and ice abrasive
* Structural fill
* Unstabilized road base

Uses of Boiler Slag

* Snow and ice abrasive
* Road base aggregate
* Ingredient in anti-skid bituminous wearing course
* Sand blasting grit

Note: FGD materials are presently not widely used in highway construction.

cover and the use of surface vegetation eliminate the dusting problem. The problem of dusting must be considered if ash mixtures are used.

2.4.2.2 External and Internal Erosion

Excluding Class C fly ash, coal ash may be generally considered as cohesionless materials. The only forces that can resist particle movements are frictional in nature. Erosion is a natural mass transporting phenomenon that is caused by wind or water. Wind and rains can lead to serious erosion problems for exposed ash on embankment sides. Cohesive soils with vegetation coverage are typically used to control the surface erosion problem and provide an aesthetic view (DiGioia et al. 1986). Appropriate encasement of the ash inside a system of base liner and a cover can significantly minimize water infiltration and internal erosion of the ash. The system consists of low hydraulic conductivity soils or synthetic materials plus filters. The efficient compaction of ash mixtures can reduce their permeabilities and consequently the internal infiltration.

2.4.2.3 Leaching

If water is infiltrated into the ash fill, leachates generated in the ash mass may be transported to the surrounding environment including the soil and the ground water. Major concerns are to be raised if the leachates contain deleterious substances at concentrations that can have adverse effects on the environment.

The chemical composition of the ash is generally inert. It consists mainly of oxides of silicon, aluminum, calcium, and iron. Minor proportions of compounds of titanium, potassium, sulfur, and magnesium may also exist. Trace elements such as compounds of barium, nickel, arsenic, silver, cadmium, lead, mercury, etc.. may also be contained in the ash in very minimal proportions (GAI and USIFCAU 1993). The Indiana Department of Transportation has restrictions on the use of coal ashes based on the type of their leachates as defined by Indiana Administrative Code, 329 IAC 2-9-3. Table 2.10 displays the criteria for defining the types of leachates based upon the levels of concentrations of the substances included in these leachates (the values included in

Table 10 may be changed in the future, thus the current values in the original reference must be consulted). Only the ashes classified as types III and IV are used in highway construction in Indiana. The utilization of type II is restricted (based upon the PH level) and type I is not allowed due to the potential for finding hazardous levels of concentrations in the leachates. Trace elements concentrations in the coal ash vary due to both depositional and post depositional conditions of the coal, the combustion procedure, ash type, technique for ash collection and transportation to disposal, the duration of contact between the ash and the emitted gasses, and the disposal and post disposal conditions. It is not simple to predict the concentrations of the trace elements in the ash leachates. The chemical analysis of the parent coal is not alone sufficient. Nevertheless, it is informative to perform it since it can reveal the noncombustible substances existing in the coal.

Tests were developed to investigate the impacts of the leachates on the environment (Jackson and Sorini 1987; USDOC 1988). The main objectives were to find the concentrations of the deleterious elements in the leachates and to define if the ash is hazardous or not. Solid wastes were classified under EPA's Resource conservation and restoration Act, RCRA, regulations (EPA 1990). Under RCRA, a solid waste is to be considered hazardous if it fails any of the criteria established for ignitability, corrosivity, reactability, or toxicity (RCRA Subtitle C; EPA 1990). Coal ashes are not considered ignitable. Types III and IV are considered neither corrosive nor reactive (USDOC 1988). Ke (1990) suggested levels of resistivity, PH, soluble chloride content, and soluble sulfates for non corrosive bottom ashes. According to these levels Huang and Lovell (1993) reported, based upon laboratory tests, that 7 out of 11 Indiana bottom ashes, tested in the laboratory, were found to be potentially corrosive. They recommended that adequate protection must be provided to any metal structure placed within the vicinity of a potentially corrosive ash. The main environmental concern is the level of concentration of the deleterious substances in the ash leachate in comparison to the levels indicated by the EPA regulations for toxicity. Tests such as the EP (Extraction Procedure) test and the Toxicity Characteristic Leaching Procedure (TCLP) were developed to determine the degree of hazard associated with leaching from waste disposal

Table 2.10 Indiana Administrative Code Restricted Waste Site Type Criteria
Indiana Adminstrative Code, 329 IAC 2-9-3
(IAC 1993)

Parameter	Concentrations (Milligram per Liter)			
	Type IV	Type III	Type II	Type I
(1) For Parameters Using the EP Toxicity test: *				
Arsenic	≤0.05	≤0.5	≤1.25	<5.0
Barium	≤1	≤10	≤25	<100
Cadmium	≤0.01	≤0.1	≤0.25	<1.0
Chromium	≤0.05	≤0.5	≤1.25	<5.0
Lead	≤0.05	≤0.5	≤1.25	<5.0
Mercury	≤0.002	≤0.2	≤0.05	<0.2
Selenium	≤0.01	≤0.1	≤0.25	<1.0
Silver	≤0.05	≤0.5	≤1.25	<5.0
(2) For parameters using the Leaching Method Test:				
Barium	≤1.0	≤10	≤25	**
Boron	≤2.0	≤20	≤50	**
Chlorides	≤250	≤2,500	≤6,250	**
Copper	≤0.25	≤2.5	≤6.25	**
Cyanide, Total	≤0.2	≤2.0	≤5.0	**
Flouride	≤1.4	≤14	≤35	**
Iron	≤1.5	≤15	**	**
Manganese	≤0.05	≤0.5	**	**
Nickle	≤0.2	≤2.0	≤ 5.0	**
Phenols	≤0.3	≤3.0	≤7.5	**
Sodium	≤250	≤2,500	≤6,250	**
Sulfate	≤250	≤2,500	≤6,250	**
Sulfide, total	≤1***	≤5.0	≤12.5	**
Total Dissolved Solids	≤500	≤5,000	≤12,500	**
Zinc	≤2.5	≤25	≤62.5	**
pH (Standard Units)	6 - 9	5 - 10	4 - 11	**

*IDEM allows EP toxicity test or TCLP test.
**Testing is not required.
***If detection limit problems exist, please consult the office of solid and Hazardous waste for guidance.

(Jackson and Sorini 1987). Leachates from coal ash rarely reach hazardous levels (USDOC 1988). The utilization of coal ash mixtures has advantages over a single type since hydraulic conductivity of the coal ash can be lowered to minimize the rate of leachate generation. Meanwhile, the stability of the ash mixtures can be maintained. The use of ponded ash may have an advantage over the freshly generated ash. The disposal procedure includes flushing the samples with water. This may reduce the concentrations of the elements attached on the surface of the ash particles.

Encasement of the coal ash embankments can minimize the infiltration of water into and out from the ash. In addition to the encasement, a sitting criteria is normally developed to provide a safety distance from the ash body (This criteria does not apply to type IV ash) to water resources (surface or ground). Although this criteria is mainly decided to protect the environment, the geotechnical aspects of the proposed site may also dictate additional measures. Factors such as the hydraulic conductivity of the surrounding soil in the site and the potential for having problems due to unfavorable soil conditions must be considered.

2.4.3 Considerations For Coal Ash Utilization In Embankment Construction

A successful project is one in which the best use of the available resources is made. It must serve the physical purposes of the project within the limitations imposed, and to achieve the intended performance levels. Coal ashes, being no different than other engineering materials, have their advantages and limitations. Successful design and construction procedures would employ the material advantages and provide provisions that would minimize or diminish the limitations effects.

2.4.3.1 Design Considerations

In general the design plans have to satisfy the highway requirements, usually the elevations and embankment top width. The requirements for safe environmental performance must also be satisfied. All the site specific conditions including the geological, hydrological, and topographical conditions have to be taken into consideration in the design. The durability and soundness of the material have to be sufficient to stand

under the expected environmental and loading conditions as long as the structure exists. Furthermore, the material has to be reasonably simple to utilize in construction. The construction materials, being coal ashes in this case, must be compacted adequately.

The fill must sustain its own weight plus the loads imposed upon it without excessive deformations within the possible site weather (environmental) and loading conditions. The compressibility of the fill has to be acceptable. The slopes of the embankment must be adequately stable. This particular consideration is directly related to the appropriate assessment of the shear strength of the material. The shear strength of the ash mixtures may possibly change with changes in the mixture proportions. The stress-strain behavior may also change. Possible differential settlements may have to be within acceptable levels. The embankment height in combination with the fill weight must not impose excessive stresses on the foundation beyond the bearing capacity or beyond acceptable compressibility limits. The unit weight of compacted coal ash mixtures are lighter than most soils. This property can be used beneficially in the design. If representative parameters are developed in the laboratory or by field testing, software packages may be used for modeling the fill deformations and stability.

The detailed design must provide provisions for the drainage of surface water and groundwater in addition to the control of capillary action is necessary to prevent ash saturation. Ash saturation may lead to frost susceptibility or liquefaction problems in addition to the environmental problems due to leaching (DiGioia 1994). The placement criteria normally contain provisions to maintain adequate distances between the ash and the drinking ground water (DiGioia et al. 1986). Appropriate encasement to minimize migration of water in and out of the fill have to be considered in the design. Any special provisions needed, for providing adequate protection of metals from corrosion and adequate protection of concrete from sulphate attack, have to be included in the design. Alternatives to metallic components such as fiber glass or PVC may be considered to avoid corrosion. Use of stainless steel parts or providing protection using special coatings may also be considered (Huang and Lovell 1993). It is also possible to use barriers of compacted soils that have very low hydraulic conductivity or geosynthetics liners to prevent the physical contact and the migration of leachates.

2.4.3.2 Construction Considerations

a- Site Preparation

The site preparation constitutes all the works required before the fill placement. This includes diverting existing drainage, dewatering low areas, removal of trees and brushes, removal of top soil, placement of drainage blankets and drains, and completion of subsurface constructions.

b- Fill Transportation and Stockpiling

The coal ash has to be transported from utility plants to construction sites. Covered dump trucks are usually used for transporting moistened coal ash to control moisture loss and to avoid dusting. If dry fly ash is transported, special pneumatic tankers similar to those used in transporting bulk portland cement are used to avoid dusting. Huang (1990) expressed the feasible distances for coal utilization to be contained by a circle with a radius that is a function of the transportation expenses as well as the price for aggregate supply. Best value usually occurs if the ash borrow source is near to the site. Stockpiling in the field is important. Sufficient quantities of ash has to be stockpiled in the site to feed any surge needs in the construction process and to serve as a contingency. The stockpiled materials have to be covered or watered to prevent dusting.

c- Fill Placement and Compaction

Detailed specifications for placement and compaction of fly ash were reported (DiGioia et al. 1986; Brendel et al. 1988; DiGioia 1994). The coal ash is usually placed in loose lifts in the range of 20 to 30 cm (8 to 12 inch) thick using a dozer. A vibratory roller may be used to compact the lifts. Pad-foot and smooth-drum vibratory rollers were used successfully to compact fly ash efficiently (Digioia 1994). Vibration frequencies in the order of 1800 to 2000 cycles/min were reported (DiGioia, 1994; Brendel and Glogowski 1989). Smooth-drum vibratory roller was used efficiently for the compaction of Schahfer bottom ash in the I-12/Kennedy project. The surface of the ash must be protected from dusting.

d- Performance monitoring

Concerns about the performance or for purposes of demonstration may lead to the installation of instrumentation to monitor performance. The structural performance may be monitored using vertical and horizontal inclinometer, settlement plates, extensiometers, and piezometers. Inspection wells can be installed for monitoring the ground water table conditions. Periodic collection and analysis of leachate samples may be performed for environmental purposes.

2.4.4 Field Performance of Coal Ash in Embankments

2.4.4.1 East Street Valley Expressway, Pennsylvania

As part of the continuous effort to promote the use of coal combustion by products (CCBP's) in highway construction, the Pennsylvania Department of Transportation (PaDOT) and the Federal Highway Administration (FHWA) agreed to use Class F fly ash and Poz-O-Tec (mixture of lime, Class F fly ash, and FGD) in a large embankment construction. The project was sponsored by Duquesene Light Company and Electric Power Research Institute (EPRI) in cooperation with the Federal Highway Administration (FHWA) and the Pennsylvania Department of Transportation (PaDOT). Necessary review for environmental impacts were performed by the Pennsylvania Department of Environmental Resources (PaDER). The East Street Valley Expressway embankment was constructed, during 1987-1988, along a section of Interstate I-279, Pittsburgh, Pennsylvania. The embankment had an average width of 210 feet, an average depth of 50 feet and an approximate length of 1490 feet. A total of 255,000 cubic yards (approximately 353,000 tons) of CCBP's were utilized in the construction (Brendel and Glogowski 1989; DiGioia 1994)

The laboratory and field investigations included both environmental and geotechnical testing programs. The environmental testing, including the EP toxicity and leachate testing, focused on the leachate composition and their impacts on the water quality. The geotechnical investigations showed that the ground water was approximately 9 feet below the valley bottom. However, concerns were raised because the side slopes of the valley were found to contain ground water as well. Adequate encasement of the

ash fill had to be implemented in the design. Figure 2.15 displays a typical cross section for the embankment and the valley.

Class F fly ash was mainly retrieved from the disposal pond of Duquesne Light Company's Cheswick Power Station. A small part was supplied from silos. The overly wet fly ash from the pond was initially placed on top of a two feet thick layer of bottom ash to drain the excess moisture by gravity. The saturated ash displayed surface instability. Additional drying was achieved using rolling blades and aeration until the moisture content of the fly ash became within the specified limits. The ash was then transported to the construction site. The silo dry fly ash was moistened upon discharge from the silos, loaded into trucks, and transported to the site. The placement of the CCBP materials followed the typical PaDOT procedures specified for natural soil placement (Brendel and Glogowski 1989). The material was dumped, spread in loose lifts of 8 in., compacted using 4 to 6 passes from a 20 ton dual pad foot vibratory compactor near a resonant frequency of 2000 VPM. The material was compacted to a minimum of 97% of maximum dry unit weight as determined by ASTM D 698, Method B. It was noted that more passes were required to achieve the targeted unit weight when the moisture content was significantly lower than the optimum moisture content. At the optimum, four passes or less were adequate to achieve the required unit weight. At excessively wet weather, loss of strength was experienced in the exposed layers. Drying of these layers was necessary before the recompaction was performed.

The field unit weight was monitored using the nuclear density gauge. The Speedy method, and the microwave oven were used along with the conventional oven for the determination of moisture contents and the dry unit weight for parallel samples retrieved using the sand cone method. The sand cone and the conventional oven method were used to calibrate the other methods and develop correlations. The results of the compaction tests were accumulated and used for the construction of a family of compaction curves for the materials encountered. Subsequently, the one-point technique for compaction control was applied. The embankment performance was monitored using settlement

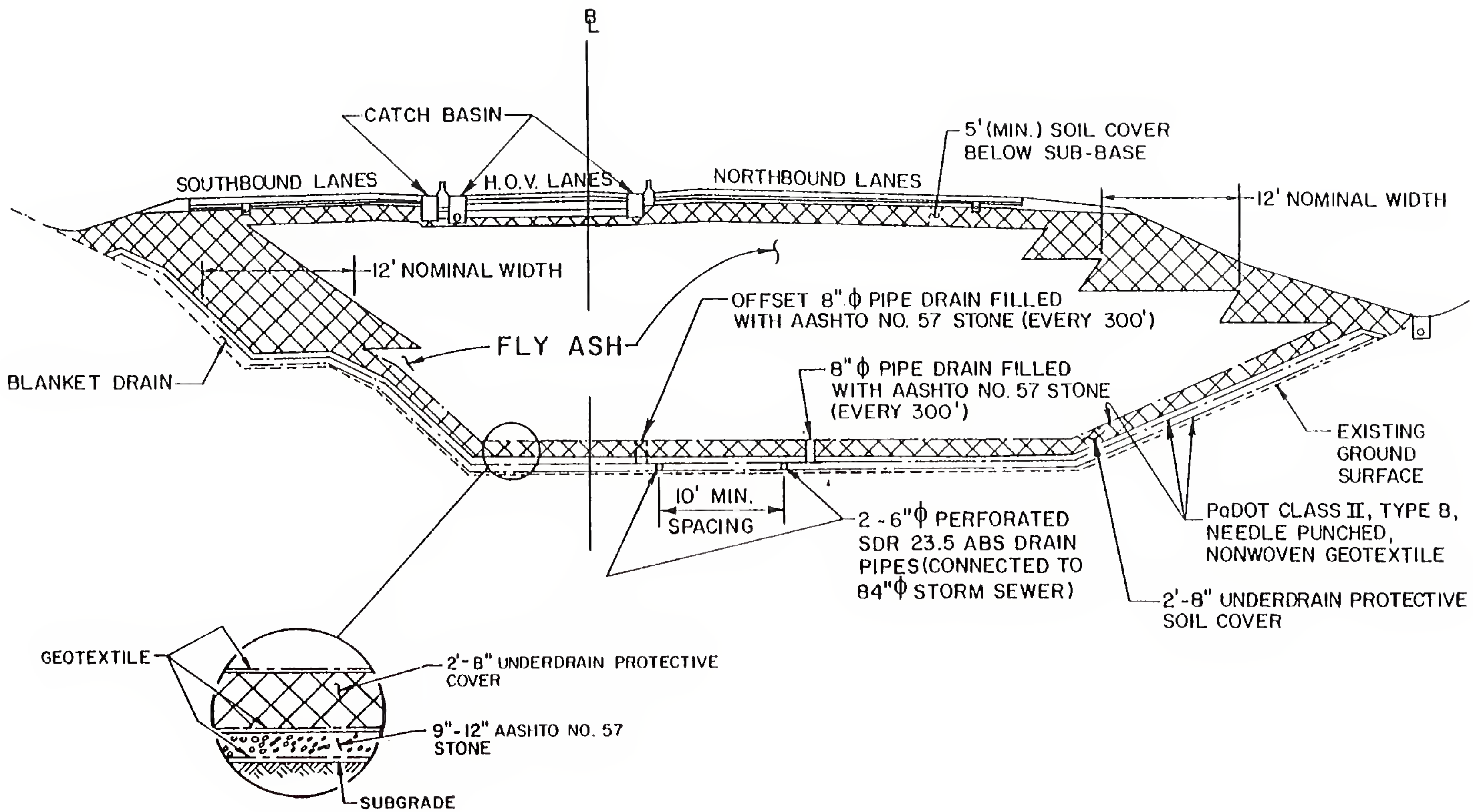


Figure 2.15 Typical Section in East Street Valley Expressway Embankment, Pennsylvania. (Brendel and Glogowski 1989)

plates, horizontal slope indicators, and piezometers. Nearly all of the settlement of the fly ash embankment occurred rapidly during the construction period. The predicted post construction settlements of 3 in. overestimated the measured settlements. It was reported that the actual field relative compaction approached 100% and the prestress due to compaction exceeded the embankment fill stresses, hence the settlements were overestimated. The project demonstrated the success of using fly ash as structural fill materials.

2.4.4.2 U.S. 12 Demonstration Project, Lake County, Indiana

As one of the major coal ash producers in the United States, Indiana has found it necessary to develop utilizations for coal combustion products to minimize their disposal problem. One of the early experiences of Indiana Department of Transportation (INDOT) on using coal ash in highway construction is raising the bridge approach along U.S. Route 12 (Columbus Drive) at the intersection with Kennedy avenue. The old embankment on this highway needed to be raised using steep side slopes (2H:1V) due limitations on the right of way (Davis et al. 1995). About twenty three thousand tons of bottom ash were supplied from NIPSCO's Schahfer power plant to be placed in this project. The leachate testing indicated that the ash was IAC waste Type III, having less than 10 % of the hazardous waste concentrations defined in RCRA.

The ash was transported using open dump trucks. Loose lifts of 8 in thickness were placed using a dozer and a grader. The bottom ash lifts were then compacted, using a vibratory smooth wheel roller (Figure 2.16), to a final thickness of approximately 6 in. The compacted dry units weight were not sensitive to the compaction moisture contents except at very low moisture where bulking could occur. The bottom ash was thus flushed with a fire hose as a method to provide adequate moisture for compaction and avoid bulking. Compaction control in the field was conducted using a nuclear density gauge. Comparatively, the moisture determination was conducted using the Speedy method, the microwave oven and the conventional oven. All the methods were correlated to the conventional oven method.

Provisions for metal corrosion and concrete sulfate attack were requested by INDOT (Hoover and Zandi 1993). Protective coatings and or, suitable fill materials were used in the contact areas. Encasement of the coal ash was at the front and rear ends where concrete elements are in contact with the fill. Three feet thick layer of silty clay (till) was placed and compacted around the bottom ash. Figure 2.17 displays the utilization of glacial till in the areas of contact with concrete elements. Encasement was also provided on the north side between the bottom ash fill and the side slope. The north-side slope was constructed using coarse ballast aggregates to provide stability and build a steeper slope. Vegetation coverage was placed on top of the one side slope originally without soil coverage. The construction was completed in 1994.

2.4.4.3 I-495 and Edgemoor Road Interchange, Wilmington, Delaware.

This demonstration project was initiated as part of the Electric Power Research Institute (EPRI) effort to promote the utilization of high volumes of coal ash instead of disposal. The primary objective of this project was to construct and monitor the structural and environmental behavior of a full-scale roadway embankment containing Class F fly ash (Srivastava and Collins 1989). The project consisted of the construction of a new above grade interchange connecting Interstate Route 495 with Edgemoor Road with all the connected constructions including six new access ramps along with realignment, reconstruction, and widening of several major access roads. Freshly generated, landfilled or stockpiled Class F fly ashes, and pulverized bottom ash were utilized in construction in this project. A typical cross section is displayed on Figure 2.18. The fly ash for the embankment was provided from Delmarva Power and Light Company's Edgemoor Station, Wilmington, and Atlantic Electric Company's Deepwater station in Penn's Grove, New Jersey. The pulverized bottom ash was supplied by Delmarva.

The testing program included preliminary testing, control during construction, and monitoring after construction. Prior to construction the laboratory testing focused on the characterization and engineering behavior testing. The relatively fine grain sizes of the

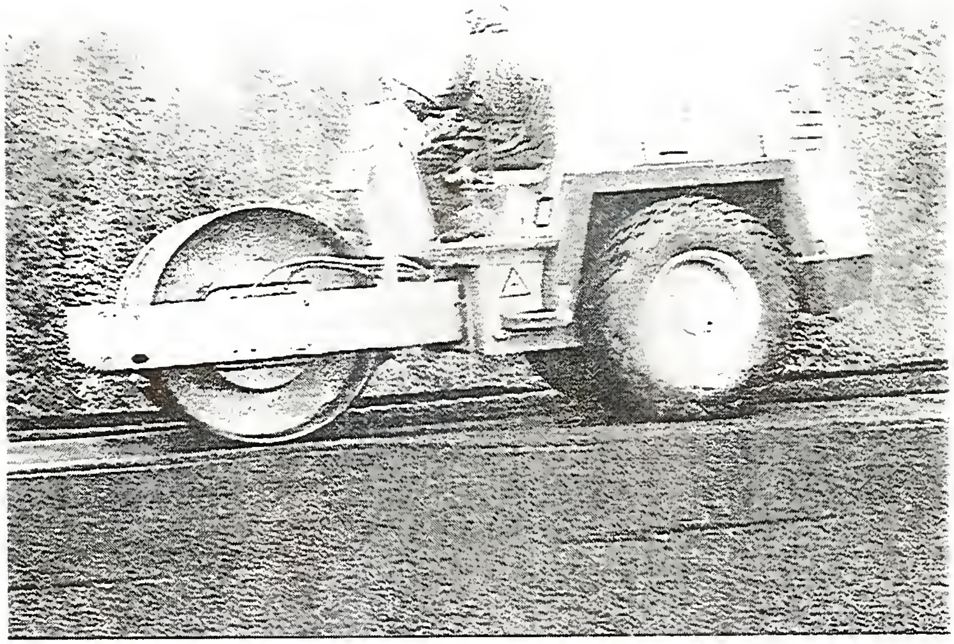


Figure 2.16 Smooth Wheel Roller Compacting Schahfer Bottom Ash in I-12 Kennedy Intersection Embankment, Indiana .

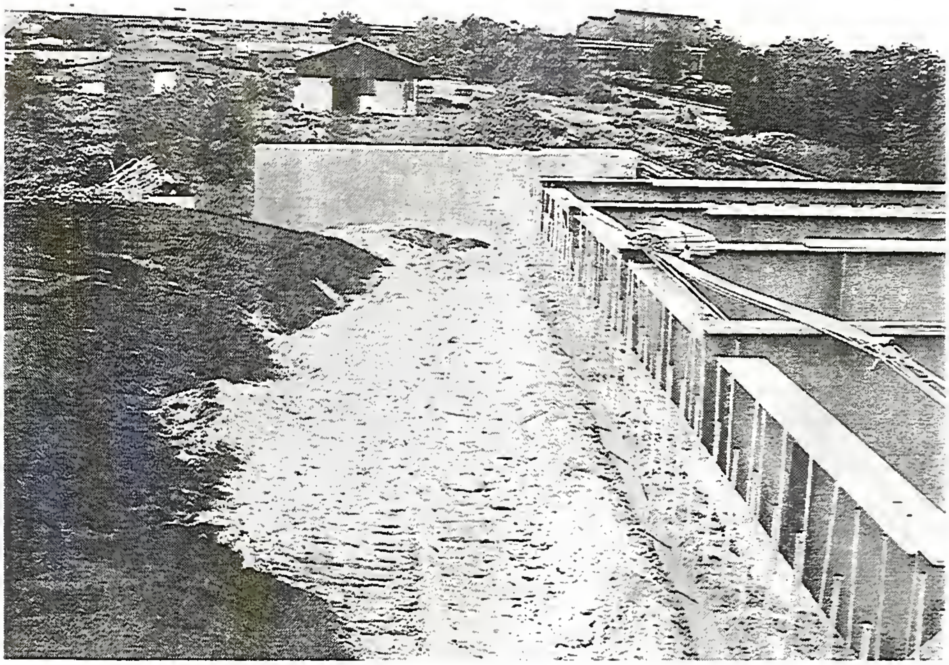


Figure 2.17 Encasement of Bottom Ash With Till at the Vicinity of Concrete Members in I-12 Kennedy Intersection Embankment , Indiana.

bottom ash used in this project were attributed to a clinker grinder that the bottom ash passed through before being disposed. Typical specific gravity values for the ashes used in this project ranged between 2.03 to 2.3. The loss on ignition (LOI) ranged between 8.17% and 11.3%. Moisture density tests were performed in the laboratory using both ASTM D-698 and ASTM D-1557. The optimum moisture content of the stockpiled ash was reported to vary with changing the sampling location within the stockpile. The permeabilities of the compacted fly ashes were found in the range between 10^{-4} and 10^{-5} cm/s. Compacted bottom ash samples were more permeable in the range of 10^{-3} cm/s, although having relatively fine gradation.

One-dimensional compression tests on the compacted bottom ash samples displayed smaller compression indices than fly ash samples. It was thus concluded that the bottom ash would undergo significantly lower settlements than the fly ash. Triaxial tests were performed according to ASTM D 3397. Angles of shearing resistance for the fly ash were reported within the range of 17° To 18 which was considered to be relatively low. Bottom ash samples displayed an angle of 34.5° which is comparable to loose well-graded sand.

The principal considerations during construction were the control of moisture content, and the control of compaction. The moisture was adjusted to avoid dusting and facilitate the compaction. Too much moisture caused loss of strength and pumping while too little moisture caused dusting and difficulty to achieve proper compaction. The field densities were measured using a Troxler density gauge. The results based on back-scatter measurements were found in agreement with those based on 8 inch probe penetration (Srivastava and Collins 1989). The back-scatter technique was thus used for compaction control during construction. The higher energy from the modified proctor density was found to have minor difference from the densities achieved by the standard proctor. Specifications for field compaction were established to achieve at least 95% of maximum unit weight, reached in the laboratory, based on standard proctor tests, ASTM D-698. The moisture contents for the samples retrieved from the field compacted fill were determined using the Speedy technique and the microwave oven. The nuclear density gauge measurements were adjusted based upon the Speedy and the microwave results.

Corrections for the nuclear gauge measurements were necessary. The accumulated results from the moisture-density tests were utilized to construct compaction curves. Subsequently, the control of the compaction in the field was performed using one-point method (Figure 2.19).

After construction monitoring demonstrated several significant results that helped the overall judgment on the success of this project. Standard Penetration Tests (SPT) were performed on the compacted fill to asses the bearing capacity of the fill. SPT values ranged between 24 and 61 blows/foot were reported. Similarly, SPT's were conducted on compacted granular fill. The results for both materials were found to be very similar. Settlement monitoring have shown negligible long-term settlements. Most of the settlements occurred during construction. Frost susceptibility testing were planned to be completed after the end of construction on fly ash and granular fill materials for comparison.

To monitor the environmental impacts of the ash fill four monitoring wells were installed. Ground water monitoring was achieved by retrieving and analyzing water samples from each well. It was concluded, based upon leaching tests and the analysis of samples collected from the field, that the fly ash utilized for this project was environmentally safe.

It was concluded that the compaction moisture was the key point for successful placement and compaction of the fly ash (Srivastava and Collins 1989). The laboratory moisture-density tests were used successfully to define the field placement moisture contents. Compacted fly ash could support heavy construction equipments without excessive rutting or damage. The dusting from poorly conditioned fly ash was found comparable to dusting from natural soils. The bearing capacity characteristics from fly ash in this project was reported to be comparable to those of well-graded sand and gravel. Overall findings supported the use of fly ash as an embankment construction material from the engineering and environmental points of view.

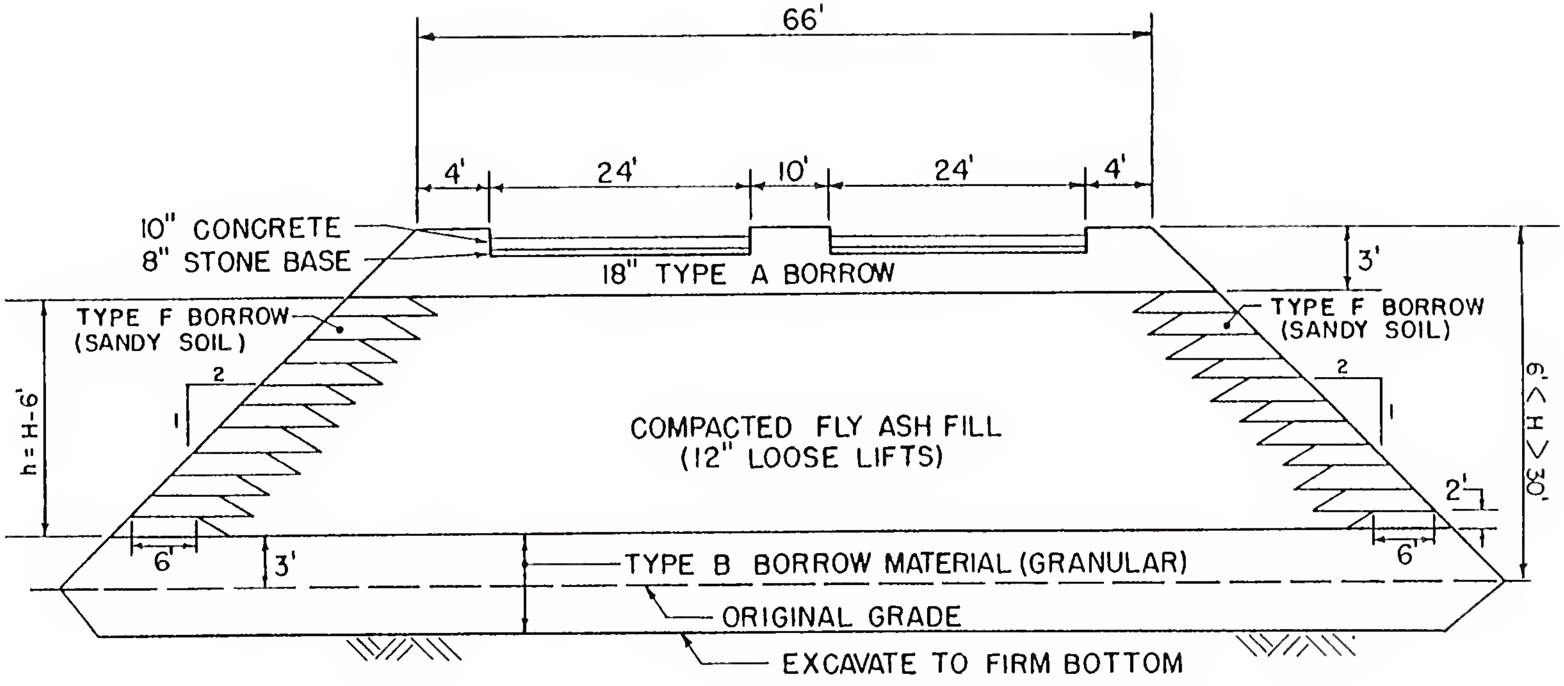


Figure 2.18 Typical Fly Ash Ebankment Section in the I-495 and Edgemoor Road Interchange, Delaware. (Srivastava and Collins 1989)

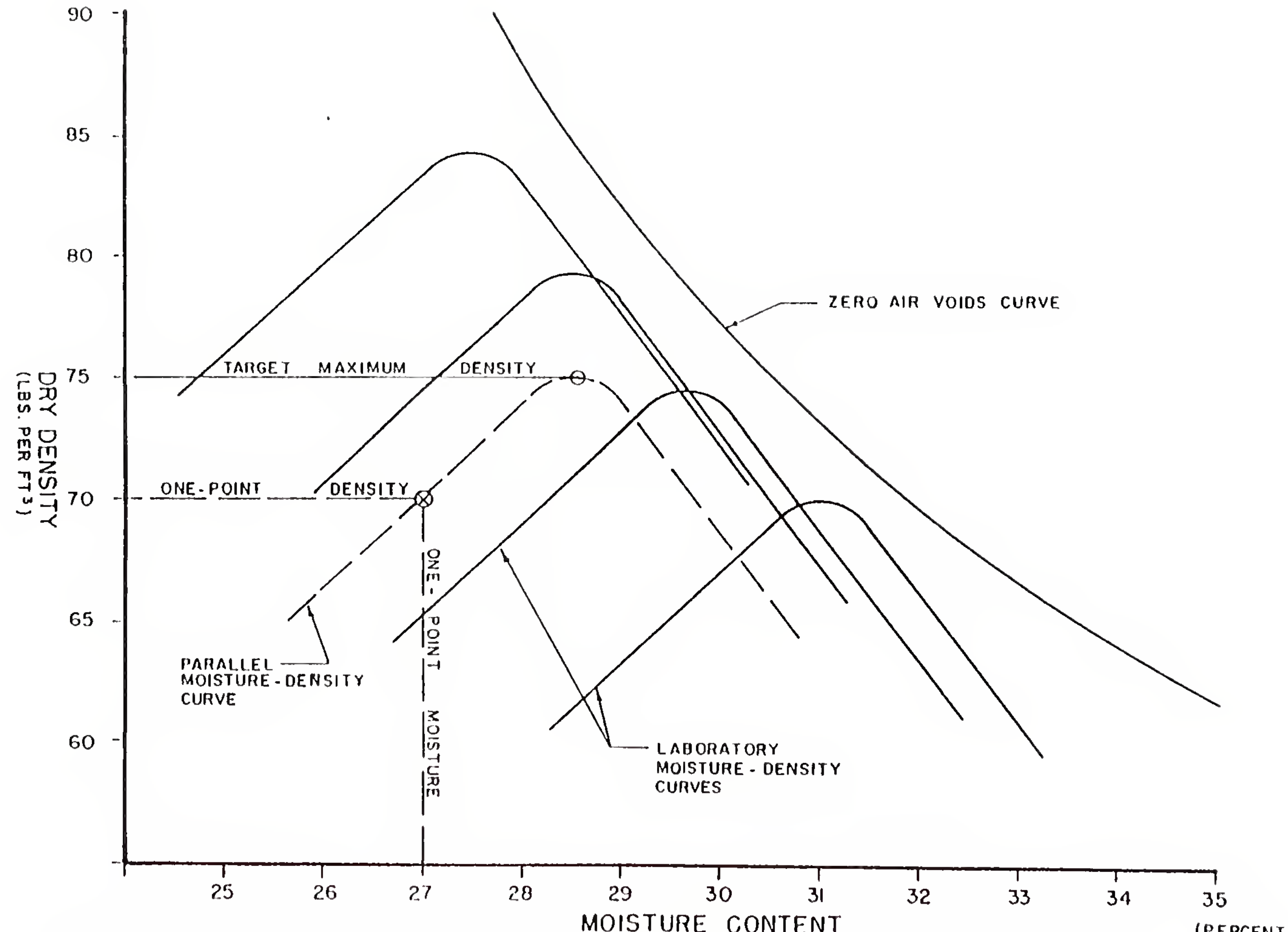


Figure 2.19 Determination of Maximum Dry Density Value from One-point Standard Compaction Test in the I-495 and Edgemoor Road Interchange, Delaware. (Srivastava and Collins 1989)

CHAPTER 3
EXPERIMENTAL APPARATUS AND PROCEDURES

3.1. Ash Sampling and Initial Processing

3.1.1 Samples Sources

Coal ash samples used in the present study were extracted from two power plants in Indiana. The first power plant was the Schahfer power plant, located in Jasper county and owned by the Northern Indiana Public Service Co. (NIPSCO). At the Schahfer plant, the ash is disposed separately. The second power plant was the Gibson power plant, located in Gibson county and owned by Public Service Indiana (PSI), is the largest power plant in Indiana. Bottom ash and class F fly ash are co-disposed at the Gibson power plant existing in the form of mixtures at disposal sites.

3.1.2 Ash Generation and Disposal Procedures in Sampling Sources

The Schahfer plant contains four power generating units (14, 15, 17, and 18). Unit 14 has a cyclone furnace that generates boiler slag. The boiler slag is successfully marketed. The other three units burn pulverized coal and generate bottom ash. The bottom ash is mainly disposed, which motivated its inclusion in this research. It is transported hydraulically and finally disposed on the margins of a disposal pond. Class F fly ash was initially stored in silos in dry condition. The fly ash may be marketed, used with lime to stabilize the flue gas desulferization (FGD) sludge, or disposed in a landfill. The Class F fly ash generated by units 17 and 18 is mostly disposed in landfills. This motivated its inclusion in this study.

The Gibson power plant contains pulverized coal burning units. Bottom ash and Class F fly ash are generated from burning bituminous coal in Gibson Plant. The fly ash

is separated from the emitted hot gases using electrically charged precepitators, then collected into hoppers. Two units were burning coals that had high sulfur content and thus are devised with flue gas desulferization (FGD) equipment. A minor fraction of the Class F fly ash is collected from the hoppers, moistened, and used with lime to stabilize the FGD sludge, locally on the plant site. However, the majority of the fly ash is slurried using water jets then pumped through pipes to a discharge point close to a disposal pond. The bottom ash is collected in a hopper, crushed, and pumped through pipes to be discharged at the same location of the fly ash disposal. The fly ash and bottom ash thus become mingled at the discharge location. The discharge location is connected to a disposal pond by a 300-m long discharge channel. The ash mixtures flow along the discharge channel to the disposal pond. A significant fraction of the ash settles along the channel before the flow reaches the pond. A crane with a large bucket is used to dredge the material from the channel.

3.1.3 Sampling Procedures

3.1.3.1 Sampling From Schahfer Power Plant

Sampling the bottom ash was performed in two stages. At first, six initial samples (3-5 kg each) of bottom ash were extracted at the ground level. The samples were collected from the disposal areas for units 15, 17, and 18 to provide guidance to the collection of large samples. After performing grain size analysis on these samples, it was concluded that small surface samples may not provide the best representation of the bottom ash. It was also noticed that samples from discharge locations contain mostly gravel size particles (Figure 3.1). Moreover, samples from the shallow streams formed between the discharge locations and the disposal pond contain fine materials (Figure, 3.2). Hence, at the second sampling stage, two large ash samples (about 250 kg each) were extracted from the margins of the disposal pond using a back-hoe. The bottom ash samples were extracted from depths starting at the ground surface to approximately 2.5 m (8 feet) deep. Using this method of sampling typically rendered the samples in a

Figure 3.1 Large Bottom Ash Particles Near the Discharge Point (Schahfer Power Plant).

Figure 3.2 Fine Bottom Ash Particles on the Surface of the Shallow Streams Between the Disposal Pond and the Discharge Point (Schahfer Power Plant).

disturbed condition. The samples were collected for grain size distribution testing and for reconstituting laboratory testing samples. No natural soil was encountered among the bottom ash samples retrieved. This indicated that the bottom ash depth extended beyond the depths reached by the backhoe. The bottom ash samples were stored in 50-gallon lined steel drums and transported to Purdue University. In addition to the bottom ash samples, one large sample of Class F fly ash (approximately 250 kg) was extracted in a dry condition from a storage silo. The fly ash was transported inside sealed 50-gallon, lined metal drums to Purdue University.

3.1.3.2 Sampling From Gibson Power Plant

Similar to Schahfer, surface samples were collected from the disposal site of Gibson power plant followed by the collection of large samples. To obtain representative samples of the wide range of mixtures in Gibson Plant, large samples were collected from four locations on the left bank of the discharge channel. The first sampling location (location 1) was at the discharge point. This location was expected to contain a large fraction of bottom ash content. The fourth sample was collected near the end of the discharge channel (location 4) to provide mixtures of low bottom ash content. The other two samples were collected from two intermediate locations (approximately 100m apart) along the channel. The ash samples were then transported inside sealed 50-gallon, lined metal drums to Purdue University.

3.2 Ash Characterization and Mixture Developments

3.2.1 Overview

The experimental program followed in this study aims at applying typical soil testing procedures in the characterization and testing of the ash mixtures. Some simple additional procedures were implemented as necessary to control fly ash dusting in the laboratory. Two types of mixtures were sought to be examined in this research: explicit mixtures formed from Schahfer plant ash and implicit mixtures formed from Gibson plant ash. Explicit mixtures were formed by mixing a known quantity of fly ash with a known

quantity of bottom ash. Implicit mixtures were formed by processing the ash samples from Gibson plant to produce homogeneous mixtures. The fines contents (% passing #200) in the implicit mixtures were then determined (as an alternative to determining the fly ash content).

3.2.2 Initial Processing, Grain Size Analysis, and Mixture Composition

3.2.2.1 Samples from Schahfer Power Plant

The dry Class F fly ash was mixed, then weighed and packed (3 kg) in double lined plastic bag packages. The packages efficiently maintained the dry condition of the fly ash and facilitated the handling. The packages were stored in dry conditions. Three hydrometer tests following ASTM D 422-90 were performed on the fly ash (Figure 3.3). The moist bottom ash was extracted out of the 50 gallon drums, placed in a 4′ x 6′ x 1′ wood frame lined with thick plastic sheets, and dried using hot halogen lamps. The dry bottom ash was sieved following ASTM D 422-90. Sieves of the following opening sizes were used: 9.5 mm, 4.475 mm (#4), 2.25 mm (#8), 1.125 mm (#16), 0.5 mm (#30), 0.30 mm (#50), 0.15 mm (#100), 0.075 mm (#200), and a pan. The weights of the retained ash were recorded. The bottom ash fractions were stored inside double lined plastic bags to maintain their dry condition. The grain size distribution of the bottom ash in each of the large samples was determined.

To form an explicit mixture for compaction or triaxial testing, the bottom ash was composed then mixed with fly ash. The bottom ash fraction in the mixture was formed by composing the ash fractions to obtain a gradation similar to the average gradation of the two large bottom ash samples (Section 3.1.3.1). A specific quantity of fly ash was mixed with a predefined quantity of bottom ash to form an explicit mixture of known fly ash content. The fly and bottom ash are mixed slowly by hand at first and then a specified water quantity was sprayed gradually while the mixing was continued in a mortar mixer (Figure 3.4). The moist samples were stored for 48 hours before any compaction or triaxial tests. Precise control of the materials weights and moisture led to accurate control of the moisture contents and dry densities.

Special respiratory equipment was used when necessary and forced air draft was used to clean the laboratory air after operations. The laboratory was equipped with an air suction system that passes the laboratory air through special filters before emitting it to the atmosphere.

3.2.2.2 Samples from Gibson Power Plant

The ash samples from Gibson power plant were collected in a moist condition. To process the samples and form homogeneous mixtures, two methods were examined. The first method included drying the mixtures, sieving them, then recombining the mixtures explicitly. This method, despite its seeming simplicity, created a significant amount of dusting in addition to the slowness of the process; thus, a second method needed to be developed. The second method, the sallow slurry deposition method, is a wet method. It was introduced, and examined, then implemented to reduce the large samples to smaller homogeneous samples that maintain the sedimentation features. The second method is succinctly summarized as follows: the mixtures are mixed mechanically to form a thick homogenous slurry, the slurry is transported into a large shallow container (in which it is allowed to dry) forming a "cake" (about 5 cm thick) . The dry cake is then divided into manageable size "flakes" (15 cm x 15 cm, Figure 3.5) . The dry flakes are then utilized to construct samples for compaction and triaxial tests. The method can be especially beneficial for the mixtures that contain about 40% or more of fly ash content. To examine the method, a total of 16 samples were extracted from 4 homogeneous slurry batches (four from each batch) that were prepared from a single location. The results were reasonably successful and the method, then implemented to prepare samples from the mixtures of moderate to high fly ash contents. Samples from location 1 contained a large fraction of bottom ash and a moisture content of 18% to 20%. A large sample was extracted (about 100 kg), mixed mechanically, then placed to dry in two large shallow trays. This sample did not form a slurry when it was mixed and hence, thorough mixing and careful handling were needed to avoid segregation. Samples from locations 2 and 3 contained higher fines contents (50% to 55%) and moisture contents, (25 to 30%). The ash formed a thick slurry as it was mixed. To provide homogeneous samples from these locations, the homogeneous slurry was discharged

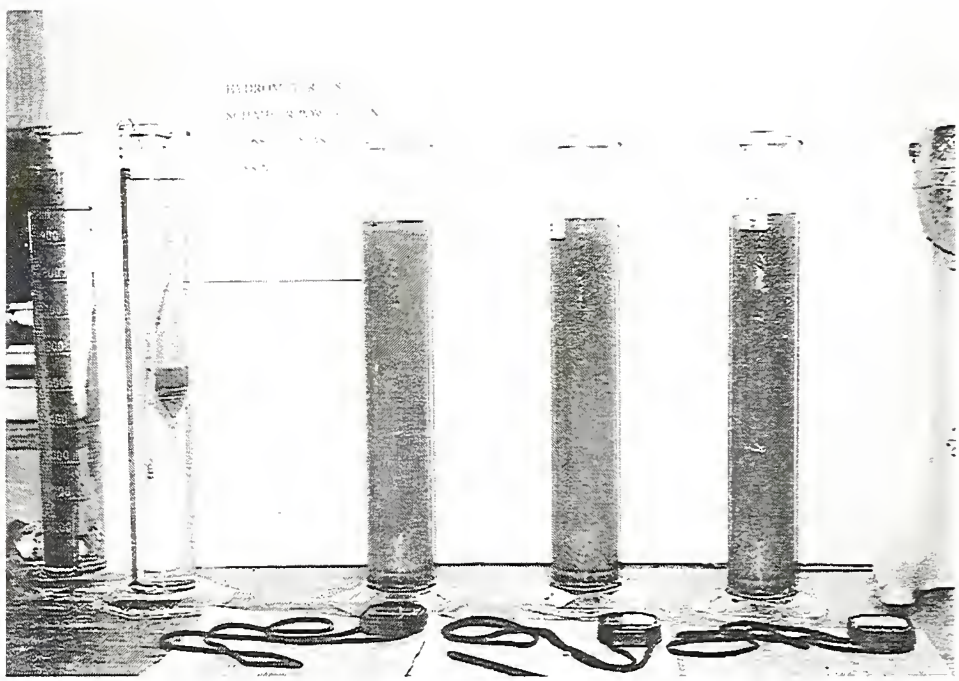


Figure 3.3 Hydrometer Tests for Grain Size Analysis of Fly Ash.

Figure 3.4 Mixing Equipment Used in Preparing Samples of Ash Mixtures for Compaction and Triaxial Testing.

Figure 3.5 Flakes of Dried Homogeneous Ash Mixtures Prepared Using the Shallow Slurry Deposition Method From Gibson Power Plant.

in a shallow large container forming a large cake. Hot lamps were used to assist in drying the slurry. To provide a sample that contained higher fines content, the particles larger than #16 were extracted from the slurry of location 4, by passing the slurry through a nest of sieves (#4, #8, and #16). The slurry was then mixed, discharged, and dried, etc., following a process similar to that of locations 2 and 3 samples. The dry "cake" from each sample was divided into dry flakes of manageable sizes (approximately 15cmx15cm). The ash flakes were stored in dry conditions. To prepare a sample for compaction or triaxial testing, a dry sample was placed in a mortar mixer and moisture was sprayed gradually during mixing in a process similar to the process used for mixing the explicit mixtures. Mechanical sieving following ASTM D 422 was used to determine the grain size distribution of the mixtures.

3.2.3 Visual and Microscopic Examination

The bottom ash and fly ash particles include a wide range of particle sizes. In order to study the surface features and the shapes of ash particles and mixtures, the ash was examined in three different ways: with the naked eye, a light microscope, and a scanning electron microscope. Examination with the naked eye was used to identify the shapes of the large ash particles (size #8 and larger), in addition to the apparent colors and features of the smaller bottom ash particles. The light microscope (manufactured by Nikon) was used to examine the particle shapes, color and surface features of smaller bottom ash particles and large fly ash particles. It was also used to study the masking effects that adding fly ash cause to the bottom ash surface features. The scanning electron microscope (manufactured by Electro-Scan, Model. 2020) was utilized to examine the shape and surface features of the fly ash particles. Using the light microscope, the magnified images were captured on photomicrographs using a polaroid camera. Using the electron scanning microscope, the images were captured on photomicrographs, in addition to digitized files.

3.2.4 Specific Gravity

Specific gravity tests as described by ASTM D 854-92 were performed on the ash samples. The method is based on liquid pycnometry (water was used in this study). The

weight of the solid particles is divided by the weight of water occupying the same volume of the solids. This necessitates removal of air bubbles from the water and particle surface pores. A vacuum pump (Duo-Seal Model No. 1405, manufactures by Sergent-Welch), powered by a ½ Hp thermally protected A-C Motor (manufactured by General Electric), was used for that purpose. The vacuum pump was capable of applying a partial vacuum of 23 in. Hg to the contents of the pycnometer. At that level of vacuum the water boils inside the pycnometer at room temperature when light shaking by hand is applied. A six valve control panel was assembled in-house to allow testing several samples at the same time. The tests were performed to determine the specific gravity of the Class F fly ash and the composed bottom ash from Schahfer. The tests were also performed on the Gibson processed mixtures of locations 1,2,3 and 4.

3.3 Compaction of Ash Mixtures

Compaction tests following ASTM D 698-91 were performed on six explicit mixtures from Schahfer power plant and four implicit mixtures from Gibson power plant. The explicit mixtures were composed as described in Section 3.2.2.1 The fly ash content (F_1) in each mixture is displayed in Table 3.1. The implicit mixtures were composed as described in Section 3.2.2.2. The fines content (F_2) in each mixture is displayed in Table 3.2. The mixtures were moistened, then left undisturbed for 48 hours so that the moisture content could equalize within the sample. The samples were then retrieved, hand mixed and compacted according to ASTM D 698. The moisture-dry unit weight curves were obtained for each mixture using, at least, five compaction tests.

Penetration tests were used to determine the appropriate range of moisture contents for compaction. When several mixtures are compacted at a single moisture content, their response to penetration will differ based on their relative compaction. If the samples are too wet, they can be penetrated easily. This indicates a moisture range that can lead to poor compaction. A hydraulically operated apparatus is the Acme laboratory penetrometer (Model CT-426 manufactured by Soil Test), normally used for testing concrete setting time (ASTM C 403-80). It is very similar in concept to the

Table 3.1 Composition of Explicit Mixtures for Compaction (From Schahfer Plant)

Explicit Mixture	Fly Ash Content F_1 %
CA1	0.0
CA2	10.0
CA3	25.0
CA4	50.0
CA5	75.0
CA6	100.

Table 3.2 Composition of Implicit Mixtures for Compaction (From Gibson Plant)

Implicit Mixture	Passing #200 F_2 %	Sampling Location From Plant B
CB1	22	Location 1
CB2	53	Location 2
CB3	47	Location 3
CB4	75	Location 4

Proctor penetration set, but, it is more accurate, is simpler to operate, and has a higher capacity gauge.

After a sample was compacted and the total weight of the moist sample plus the mold was measured, the mold was placed on the base of the penetrometer. A needle was then lowered to penetrate the sample a total distance of at least 1 in. (25.4 cm) at a rate of 0.5 in. (13mm)/s. The penetration load was recorded. After penetration, the sample was extracted out of the mold. Moisture content samples were obtained along the unpenetrated portion of the sample. The load of penetration was then multiplied by the reciprocal of the needle base area to determine the penetration pressure. Plots of penetration pressure versus moisture content were generated.

3.4 Minimum And Maximum Density

The minimum and maximum density tests were performed on dry samples of explicit mixtures with fly ash content of 25% or less. The minimum density was performed as described by ASTM D 4254-91 (Method B) standard procedures. The maximum density was determined as described by ASTM D 4253-93 standard procedures. A vertically vibrating table was used to increase the density of the dry samples in a 4-in. diameter mold. To reduce the dusting due to vibrating the fly ash, the assembly of the vibrating table, the sample and the surcharge weights were covered with double-layered plastic envelopes. Time was allowed after each time the vibration stopped for the disturbed fly ash particles to rest. The use of respiratory protection equipment during the maximum and minimum density tests of dry ash samples was necessary. Based on the minimum and maximum density values, the relative density of the mixtures can be obtained.

3.5 CID Triaxial Tests

3.5.1 Overview

In order to study the behavior of compacted ash samples in shear, isotropically consolidated, drained (CID) triaxial compression tests were conducted. In an explicit mixture

the objectives were to study the effects of changing the fly ash content and the compaction level on the angle of shearing resistance and the volumetric behavior of the specimen in drained shear. Similarly, in an implicit mixture, the effects of changing the fines content needed to be investigated. The degree of stability of a slope in an embankment may depend on the angle of shearing resistance of the compacted fill. Focus was placed on obtaining the angle of shearing resistance, since Class F fly ash has negligible cementing properties and hence the strength can be considered frictional and dilatational, rather than cohesive.

A total of 48 samples of ash mixtures were formed, compacted, saturated, and consolidated following ASTM D 4767-88, then sheared under drained conditions. Two levels of relative compaction (90 and 95%) were used per mixture. At each compaction level, three tests were performed, each at a specific confining level. Two sample sizes were used: for bottom ash and mixtures rich in bottom ash, 10 cm x 20 cm (4in. x 8in.) samples were used; for fly ash and mixtures rich in fly ash, 7 cm x 17 cm (2.8in. x 6.67in.) samples were used. The composition, size, compaction ratio R, and confining pressure σ_3' of each sample are given in Tables 3.3 and 3.4.

3.5.2 Equipment

The equipment used was the following: specimen preparation apparatus, testing apparatus, and supplementary apparatus. The following preparing apparatus were used for preparing a specimen: a mortar mixer (manufactured by Hobart), a flat top balance (Model I-10 by Ohaus), a balance (Model 3600, manufactured by Mettler), a spray bottle, plastic containers, a split mold plus a base, and a membrane expander. The testing apparatus consisted of the following: MTS Soil Mechanics Test System, triaxial cells, a pressure/plumbing control panel, a vacuum control panel, and CO_2 gas cylinders equipped with pressure regulators (Figure 3.6). The supplementary apparatus consisted of: latex membranes, a Nold water de-aerator, a vacuum pump (Sergent-Welch Duo-Seal Model No. 1405), small leveling tool, straight edge, calipers.

The MTS Soil Mechanics Test System (Modified, Model-810) is controlled by a 458.2 MTS MicroConsole using a Testlink software. The software is run on a personal

computer (Dell, SX-386) connected to the MicroConsole via a 459.16 MTS Testlink Connector Interface. This interface is also used for transferring the data, including the axial displacement, the axial load, the cell pressure, and the pore pressure, to be recorded automatically on the computer in a digitized form (on an ASCII format data file). The MicroConsole is equipped with a 458.13 AC controller for control and readout of axial displacement (using an LVDT internally mounted on the MTS hydraulic actuator Model 244.12). It is also equipped with three 458.11 DC controllers that were used in this study for readout only of axial load (using an MTS load cell Model 661.19, max load of 25 kN), cell pressure [using a pressure transducer Model TJE/708-15-01 manufactured by Sensotec, maximum pressure of 300 psi (2100 kPa)] and pore pressure [using a pressure transducer Model TJE/708-15-02 manufactured by Sensotec, maximum pressure of 300 psi, (2100 kPa)].

The triaxial test was performed using a strain-controlled mode. The axial displacement was applied by the 244.12 hydraulic actuator that was mounted on an MTS rigid loading frame. The hydraulic pressure is supplied to the hydraulic actuator from a 510.10B hydraulic pumping system. The 510.10B hydraulic pumping system is capable of pumping the hydraulic fluid (Mobil DTE 25 hydraulic Fluid) at a rate of 38.3 liter/min and a maximum pressure of 3000 psi. The hydraulic system is equipped with a strong, high efficiency, 25 hp hydraulic pump (Model JB0254DfA, manufactured by Sterling Electric, Inc.). The movement and the load produced by the hydraulic actuator are controlled by precision servo-hydraulic valves through a closed MTS loop. A maximum load of 2500 kg (5.5 kips) can be generated from this system.

To percolate CO_2 through the sample, a high pressure-low pressure regulator is used to control the percolation pressure of CO_2 before it enters the specimen. The CO_2 tubing is normally connected to the bottom platen. The top platten is usually connected to a regulated vacuum line through the vacuum regulation panel. The vacuum regulation panel contains a three way-valve, a vacuum regulator, a vacuum gauge, tubing and top and bottom platen connections.

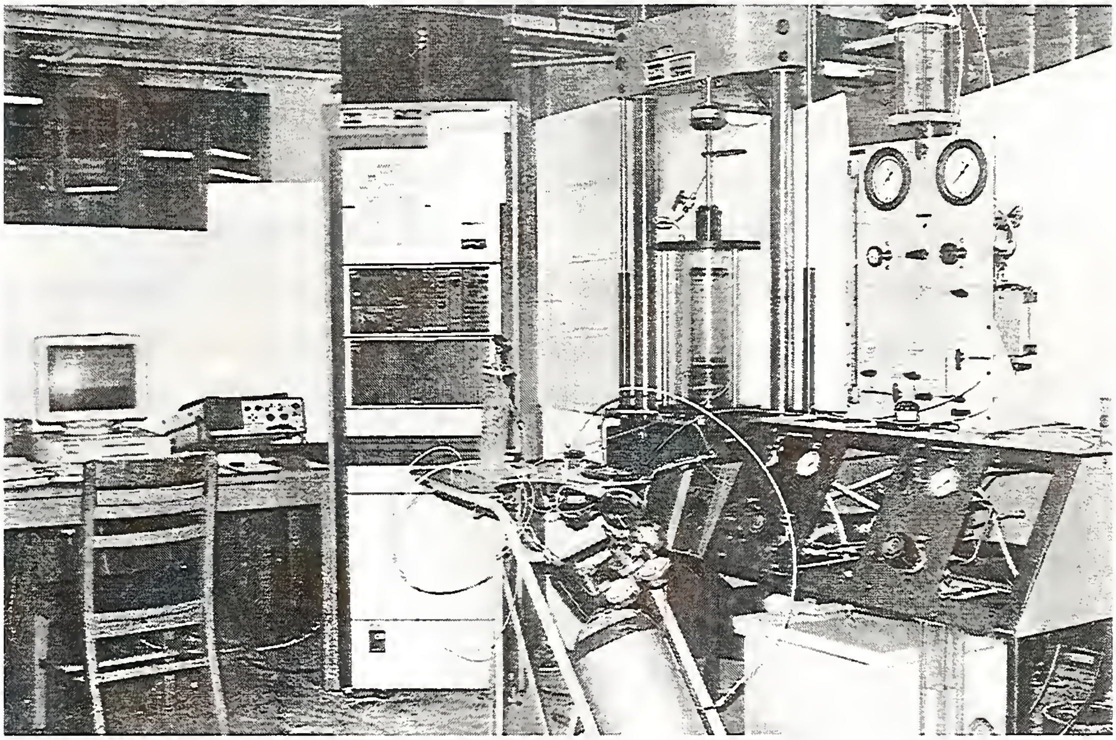


Figure 3.6 Triaxial Testing System Including MTS Soil Testing System, the Plumbing/ Pressure Control Panel, and Vacuum/CO_2 Percolation Panel.

The pressure/plumbing control panel contains the pressure regulators that control the cell pressure and the back pressure, in addition to pressure gages. It also contains the plumbing system, including a saturation tank, a volume change burette, plumbing control valves and the connecting tubings to the top and bottom plattens.

3.5.3 Test Procedure

Five explicit mixtures from Schahfer power plant and three implicit mixtures from Gibson power plant were selected to be tested. Six samples were formed from each mixture and divided into two groups. Each group contained three samples. The first group of samples was compacted using moist tamping at a relative compaction R= 95%, and the second group, at R=90%.

Each sample was compacted in a split mold in six layers inside a thin stretched membrane. The sample was then mounted on the triaxial cell base, and the top platten was mounted. A small vacuum was applied (about 4 to 5 in. Hg) through the bottom platten while the top platten valve was closed. The former was disassembled as the sample was under the vacuum. A second membrane was typically added using a membrane expander and then the cell chamber was assembled. After the cell pressure had been raised to 15 kPa, the vacuum line was switched to be connected to the top platten and percolation of CO_2 was allowed through the bottom platten. The CO_2 was typically percolated at an entrance pressure (measured at the bottom platten valve) of less than 2 psi for a period of 60 minutes. The objective was the replacement of the majority of the air bubbles in the specimen's pores by CO_2 gas bubbles.

The CO_2 line is then replaced by the bottom platten line (from the pressure control panel). De-aired water was allowed to percolate very slowly under the partial vacuum plus a small elevation head (about 50 cm), until no more gas bubbles pass through the top platten. The percolation is usually completed in 45 to 120 minutes. depending on the mixture composition and the degree of compaction. The vacuum line is then disconnected from the cell and replaced by the top platten water line (from the pressure control panel). The back pressure is then increased simultaneously with the cell pressure to keep the effective pressure on the sample at about 20 to 25 kPa. The pressures are increased very slowly in

about 30 to 60 minutes. A period of time is then allowed for the gas bubbles to dissolve in the pressurized fluid, while the sample was allowed to absorb more de-aired water. The fly/bottom ash mixtures of 25 to 75% fly ash contents were typically difficult to saturate at the maximum available back pressure supply level (500 kPa), using backpressure and deaired water only. The use of CO_2 percolation in addition to the use of de-aired water, helped obtain B parameters in the range of 0.95 to 0.99 at the normal laboratory pressure range.

The three samples in each group were consolidated to be sheared at effective confining pressures (σ'_3) of 50, 100, and 200 kPa. After specimen saturation, the cell pressure was increased until the required consolidation pressure is applied to the specimen. Out of all the groups, only one group was tested at $\sigma'_3 = 50, 100, 150$ kPa (instead of 50, 100, and 200 kPa, due to some difficulty with pressure level in the laboratory). The time for completing the consolidation was determined using two methods: the volume change versus the square root of the time and the volume change versus the logarithm of time (ASTM D 2435-90). The effect of the fly ash content and the compaction level on the volume change compressibility was examined.

Shearing of triaxial specimens was conducted under strain-controlled conditions. The rate of axial strain was determined such that the pore pressure build-up due to shear was prevented. The deformation rate, deformation amount, and the data sampling rate were entered interactively into the Testlink software display window, then the loading stage was started, monitored and terminated automatically. Typically, specimen shearing was completed in 4 to 8 hours. The pore pressure was typically monitored through one end of the sample while the drainage was allowed through the other end. The volume change was recorded manually versus the axial deformation. After the termination of each test, the total sample was dried and the dry weight was used to check the accuracy of the targeted sample dry unit weight. The samples were then stored temporarily until disposal. Each sample was stored in a plastic bag, then tagged with the specimen name and date authorizing disposal.

The axial displacement, the axial load, and the volume change were recorded automatically in a data file, as the test continued. The volume change was recorded manually

Table 3.3 CID Triaxial Compression on Explicit Mixtures (From Schahfer Plant)

Mixture	Fly Ash Content, F_1%	Compaction Ratio, R%	Sample size in.x in.	Confining Pressures σ_3' a, b, c (kPa)
TXA1H	0.0	95	4 x 8	50, 100, 200
TXA3H	25	95	4 x 8	50, 100, 200
TXA4H	50	95	2.8 x 6.7	50, 100, 200
TXA5H	75	95	2.8 x 6.7	50, 100, 200
TXA6H	100	95	2.8 x 6.7	50, 100, 200
TXA1L	0.0	90	4 x 8	50, 100, 200
TXA3L	25	90	4 x 8	50, 100, 150
TXA4L	50	90	4 x 8	50, 100, 200
TXA5L	75	90	2.8 x 6.7	50, 100, 200
TXA6L	100	90	2.8 x 6.7	50, 100, 200

Table 3.4 CID Triaxial Compression on Implicit Mixtures (From Gibson Plant)

Mixture	Passing #200, F_2 %	Compact. Ratio, R %	Sample size in. x in.	Confining Pressures σ_3' a, b, c (kPa)	Sampling Location
TXB1H	22	95	4 x 8	50, 100, 200	Location 1
TXB2H	53	95	4 x 8	50, 100, 200	Location 2
TXB4H	75	95	2.8 x 6.7	50, 100, 200	Location 4
TXB1L	22	90	4 x 8	50, 100, 200	Location 1
TXB2L	53	90	4 x 8	50, 100, 200	Location 2
TXB4L	75	90	2.8 x 6.7	50, 100, 200	Location 4

and readings were entered manually into the data file. A spreadsheet was written to import the data and perform the mathematical operations to determine the axial strain (ϵ_a), the volumetric strain (ϵ_v) and the deviatoric stress [$\sigma_d = (\sigma'_1 - \sigma'_3)$, where σ'_1 is the axial effective stress and σ'_3 is the radial effective stress], from the recorded data (Bishop and Henkel, 1962). The relationships between the deviatoric stress (σ_d) versus axial strain (ϵ_a), and the volumetric strain (ϵ_v) versus axial strain (ϵ_a) were generated. The effective stress path (q versus p') curves were developed for all the tests. The mobilized angles of shearing resistance were calculated and plotted versus the axial strain for each test. The peak angle of shearing resistance at failure [$\phi'_{max} = \sin^{-1}(\sigma'_1 - \sigma'_3)_f/(\sigma'_1 + \sigma'_3)_f$] representing the maximum strength and the critical angle ϕ'_{crit} representing the ultimate strength, were also calculated. The effects of changing the mixtures composition (F_1 ,F_2 %), the degree of compaction (R%), and the confining pressure (σ'_3) on the stress strain behavior were obtained.

CHAPTER 4
CHARACTERIZATION AND COMPACTION OF COAL ASH MIXTURES

4.1 Overview

This chapter includes results and discussion of the ash characterization and compaction. The characterization tests include grain size analyses, visual and microscopic examination, maximum and minimum densities, and specific gravity tests. This chapter also summarizes the results of the compaction of the ash mixtures. It includes discussion of the effects of changes in the mixture proportions and the compaction moisture contents on the compacted dry density. Penetration tests on the compacted ash mixtures were performed. The effects of changes in the moisture content on the penetration resistance are discussed.

4.2 Grain Size Analysis and Specific Gravity

4.2.1 Samples from Schahfer Power Plant

Initial surface samples of ponded bottom ash were retrieved from the Schahfer power plant for visual characterization and grain size analysis. The grain size distributions of these samples are displayed in Figure 4.1. Two large samples were subsequently collected. The large samples were dried, then sieved (Section 3.2.2.1) to separate the bottom ash into fractions based on their grain size. The results of the analysis of the two large samples were used to define the gradation of the bottom ash used in the explicit mixtures. The resulting bottom ash gradation is displayed as curve 2, Figure 4.1. The results show that the bottom ash gradation is for most samples similar to a well graded sand. Gravel-size particles can be found, however, in the vicinity of the discharge locations. Samples of fine gradation (fine sand to silt sizes) were found in localized surface spots in the paths of the shallow streams on the

margins of the disposal pond. Hydrometer tests were conducted on three samples of Class F fly ash from the Schahfer power plant, passing # 200 sieve (Section 3.2.2.1). The grain size distribution of the fly ash is displayed in Fig. 4.2. Explicit mixtures were composed of the class F fly ash and the bottom ash from Schahfer (fly ash contents included in Table 3.2). The grain size distribution of the explicit mixtures is displayed in Fig. 4.3. The average specific gravity values of the bottom ash and Class F fly ash samples were 2.58 and 2.41 respectively.

4.2.2 Samples From Gibson Power Plant

The grain size distribution of the initial samples collected form several locations from Gibson is displayed in Fig. 4.4. The initial sampling was followed by the collection of large samples from four locations along the discharge channel (Section 3.1.3.1). One implicit mixture was formed from each one of the four sampling locations from Gibson Plant co-ponded bottom ash and Class F fly ash. A mixture was formed by mixing and then drying a large sample following the procedures described in Section 3.2.2.2. To verify the homogeneity of the samples developed by the slurry deposition method, four samples were extracted from the dry "cake" of each one of four consecutive slurry batches from location 4 (a total of 16 samples). The samples were sieved to determine their grain size distribution. The results are displayed in Fig. 4.5. The grain size distribution of the implicit mixtures from the different locations is displayed in Fig. 4.6. The majority of the samples from Gibson Plant contained a percentage of fines that exceeded 35 %. The average specific gravity values of the implicit mixtures from location 1,2, and 4 were 2.63, 2.56, and 2.44.

4.2.3 Discussion

The grain size distribution of the bottom ash varies based upon the location of sampling. Small surface samples may not be representative of the actual gradation. The samples tested indicate that the bottom ash, in general, has a gradation similar to well graded sands. Large samples need to be processed to provide a correct representation. Oversized particles are to be found near the discharge points. Oversized particles usually complicate the compaction control. Fine particles (size of fine sand and coarse silts) found in localized spots in paths of shallow streams should be avoided when choosing materials for embankments.

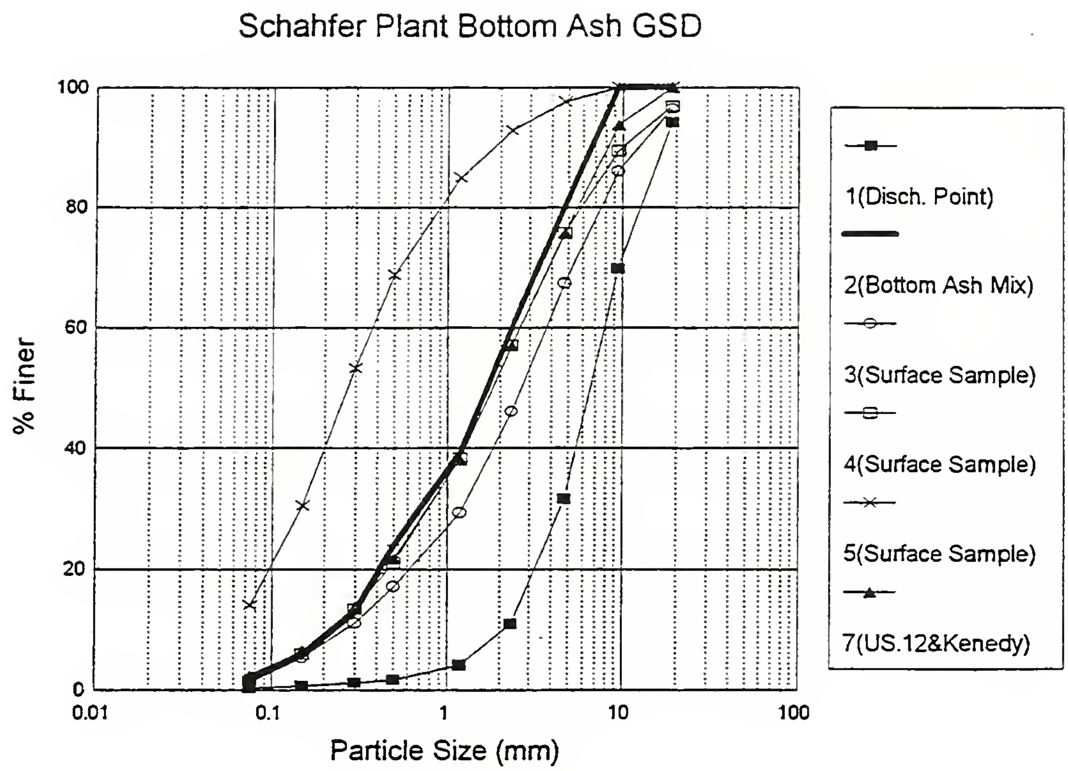


Figure 4.1 Grain Size Analysis of the Schahfer Plant Bottom Ash Samples.

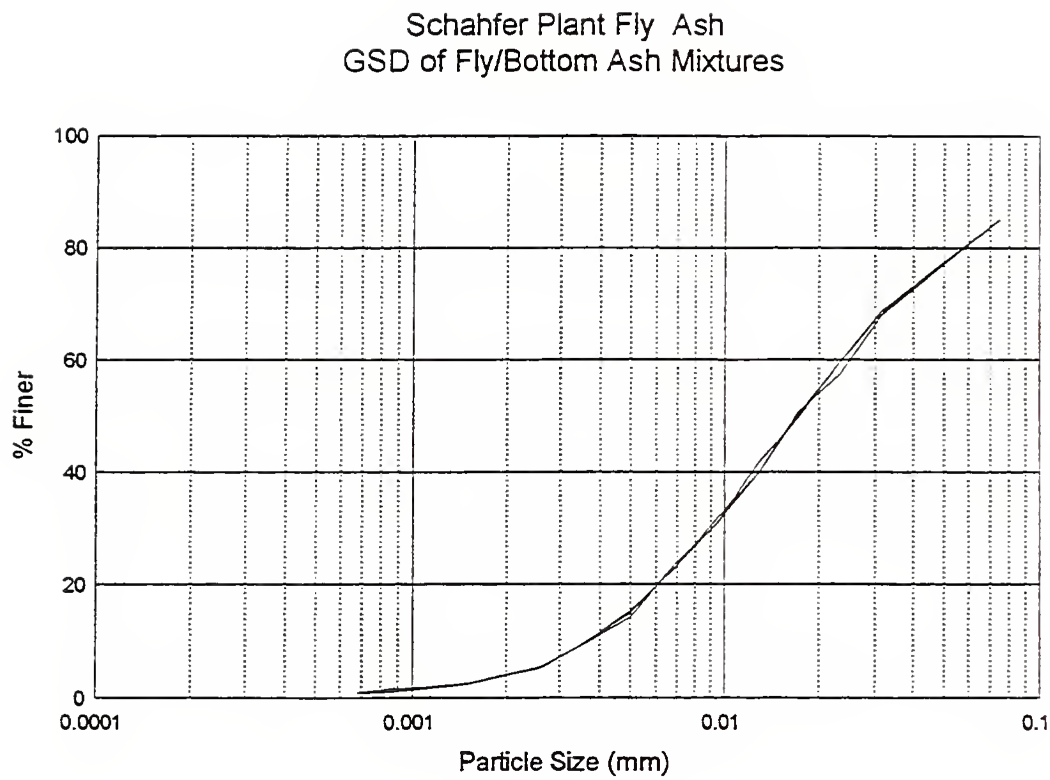


Figure 4.2 Grain Size Analysis of the Schahfer Plant Class F Fly Ash Samples.

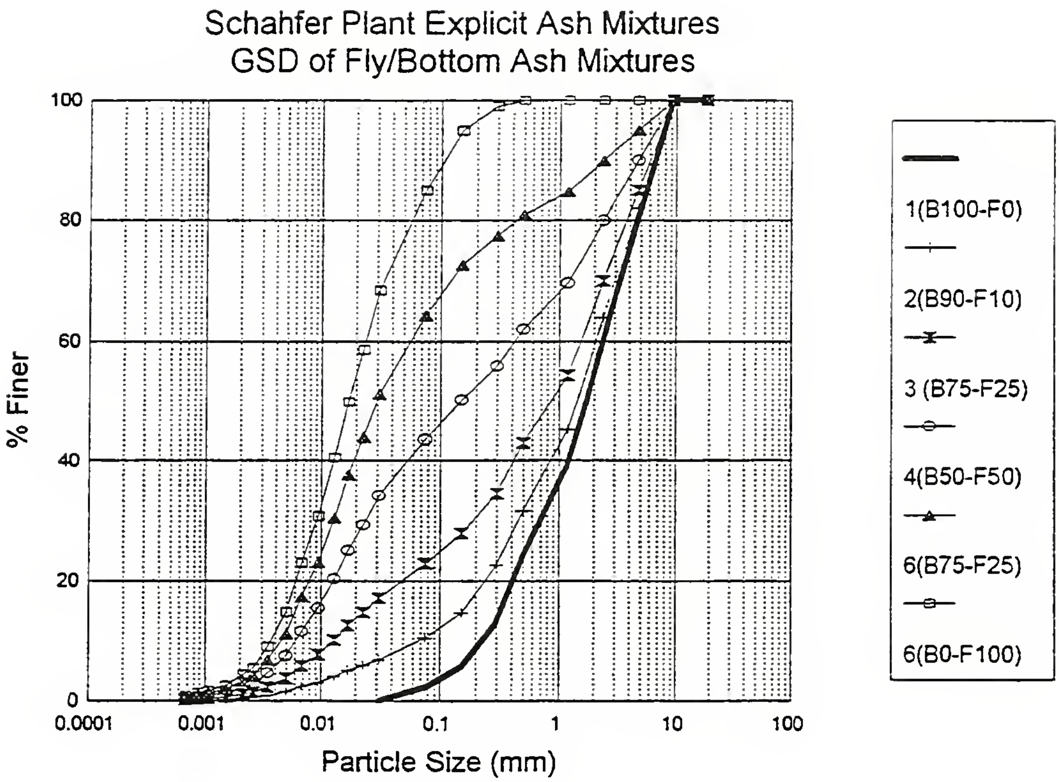


Figure 4.3 Grain Size Analysis of the Schahfer Plant Class F Fly Ash and Bottom Ash Explicit Mixtures.

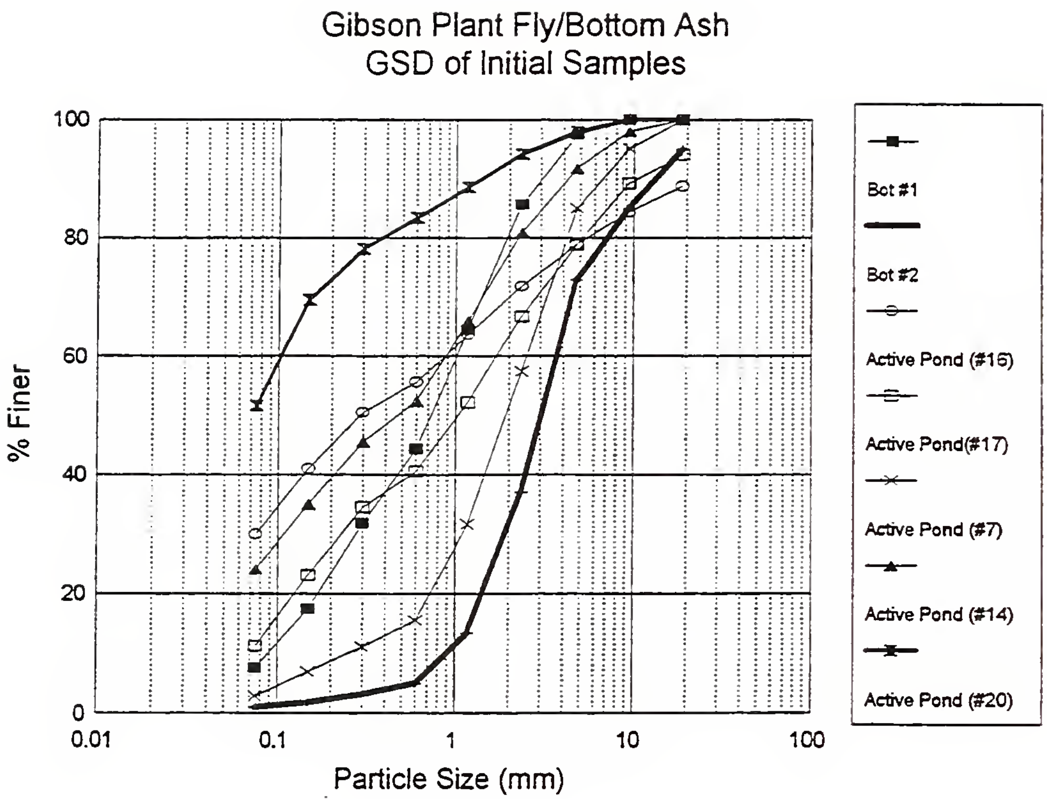


Figure 4.4 Grain Size Analysis of the Gibson Plant Initial Surface Samples of Class F Fly Ash and Bottom Ash Implicit Mixtures.

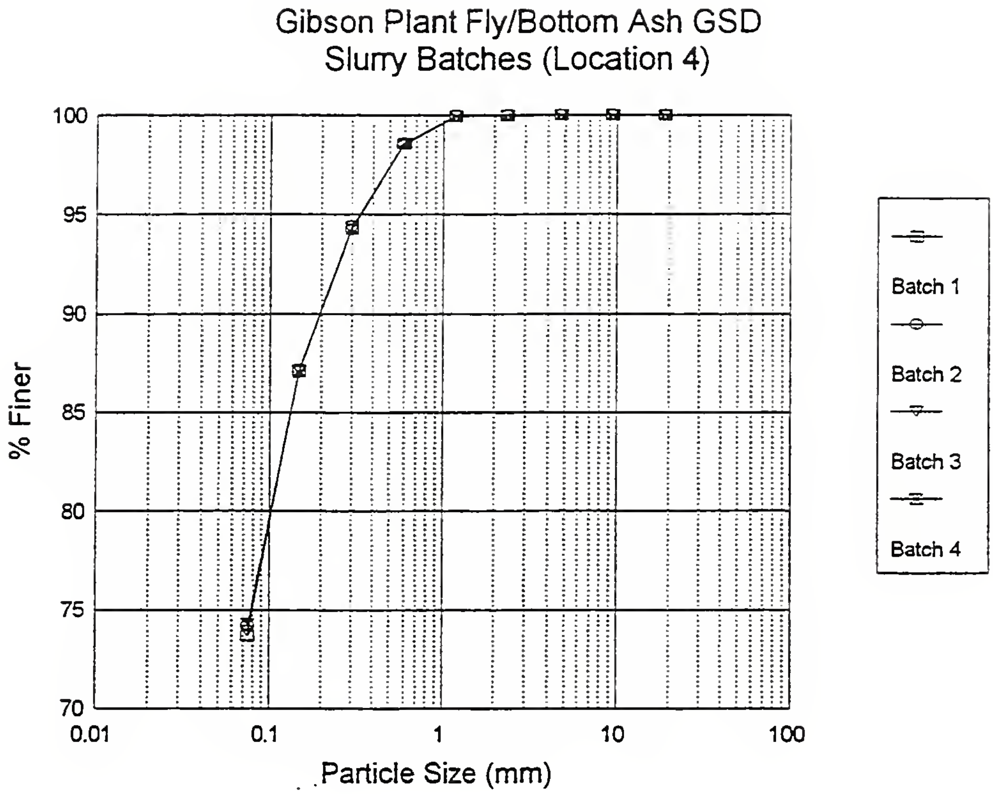


Figure 4.5 Grain Size Analysis of Ash Mixtures From the Gibson Plant, Location 4, (Shallow Slurry Deposition Method).

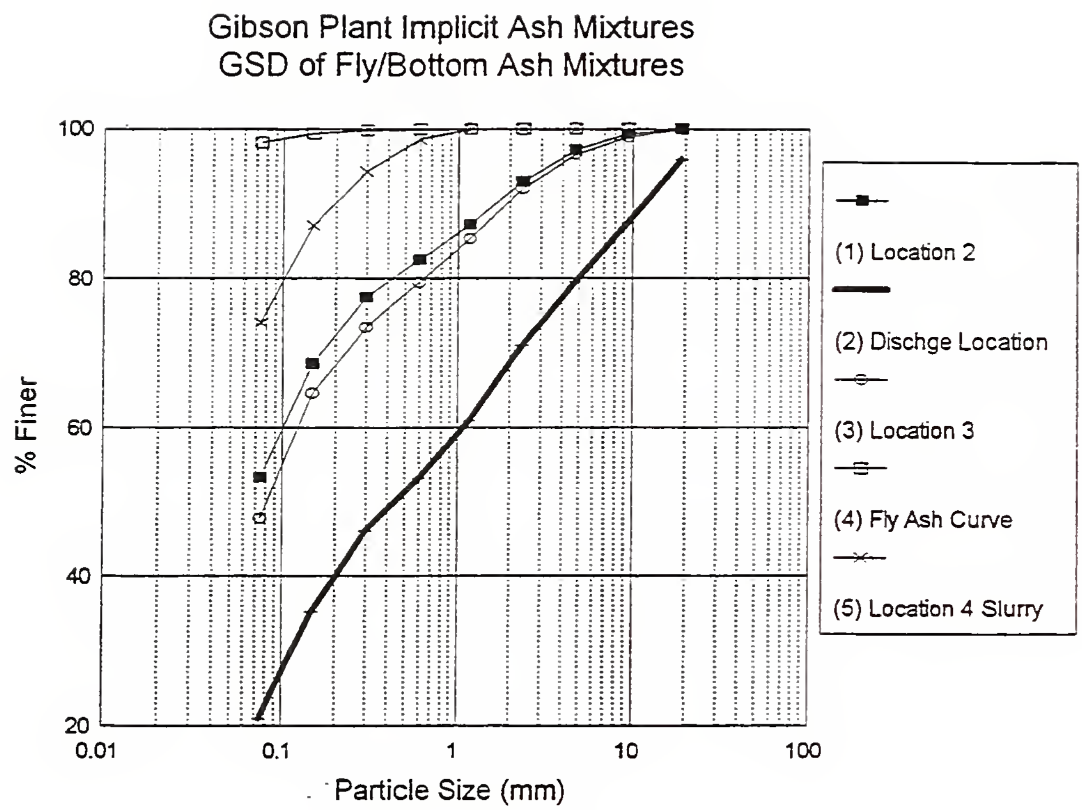


Figure 4.6 Grain Size Analysis of the Gibson Plant Bottom Ash and Class F Fly Ash Implicit Mixtures.

The grain size distribution of the implicit mixtures from Gibson display a wide range of gradations. Similar to samples from the Schahfer Plant, small surface samples can misrepresent the gradation. Surface samples are easily affected by environmental conditions. Surface flow of precipitation can transport fines from high topographic locations, leaving coarser gradations on the surface. However, if a deeper sample were to be extracted, greater fines content may be found. Large samples should be extracted and a method to reduce them should be used, for example, using the shallow slurry deposition method presented in Section 3.2.2. Due to the natural deposition process, one normally expects that the larger particles are deposited near the discharge point; meanwhile, gradually increasing fines content is expected to be found in the mixtures as the distance from the discharge point increases. The actual gradations at the site do not perfectly follow this idealization due to the variation in discharge rates, variation in the production of ash types, environmental effects on the site, and man-made transportation of the materials.

According to the results from samples tested in this research, while there was no direct accurate relation that could be established between the radial distance from the discharge point and the gradation of the ash, there were some observable trends. The sample from location 2 (100m from the discharge point) contained about 5% more fines than the sample from location 3 (200m from the discharge point). However, both samples were within a range of 50% $\pm$ 5% fines content. This suggests that improvements and innovations are needed, in the disposal process, to further control the composition of the mixtures at the disposal locations in the power plants. At present, the characterization and identification has to be dealt with each time a borrow area is chosen as a source of material.

4.3 Visual and Microscopic Characterization

4.3.1 Results

Extensive visual and microscopic examinations were performed to examine the particle shapes and surface features of fly and bottom ash particles. Samples of fly and bottom ash were inspected in three different ways: with the naked eye, a light microscope (LM) and

a scanning electron microscope (SEM). For comparison, samples of Ottawa sand, passing #30 sieve (0.5 mm) and retained on #50 (0.3 mm) were examined under the light microscope.

The fly ash particles are spherical, powder-like particles. Some particles are hollow and some particles are broken. Observed under the naked eye, their apparent color was tan to grey, but under magnification the individual particles appeared to be black, tan, brown, or colorless. Figures 4.7 (a,b) display SEM micrographs of Class F fly ash particles from Schahfer. Figures 4.8 (a,b) display Class F fly ash particles from Gibson. A magnification of x30,000 was used to scan the surfaces of single particles of 0.001 to 0.01mm diameter. The surface of the particles appeared to be very smooth. The displayed micrographs also confirm the surface smoothness for the larger particles. The Class F fly ash particles from Schahfer were less smooth than those of Gibson, especially in the larger particle range (> 0.03 mm). The magnification factors utilized ranged between x900 and x3550. The proportional scales are displayed on the micrographs. The size range also appear to be consistent with the hydrometer analysis provided earlier (Figure 4.2).

In general, a minor fraction of the bottom ash particles are finer than 0.075 mm (#200 U.S. sieve). Fine bottom ash particles, smaller than 0.075 mm (passing US sieve #200), were also examined using the scanning electron microscope. The bottom ash particles in this size range appeared to be of three types: fine fractions of shattered bottom ash particles, large spherical fly ash-like particles, and conglomerates of bonded fly ash particles. The majority of particles in this size range follows the first and second types [Figures 4.9 (a),(b)]. The first type can be easily identified by the irregular particle shape, and the gritty surface.

The majority of the bottom ash particles are significantly larger in size than 0.075 mm; the visual inspection and the magnification using the light microscope were implemented for their examination. Figures 4.10 (a,b,c, and d) display photomicrographs of bottom ash particles (retained on # 8, 16, 30, 50), sampled from Schahfer power plant, using the light microscope. The magnifications used were x10, x20, and x30. Figure 4.11 displays bottom ash particles of 0.03 mm in size, from Gibson mixtures. These bottom ash particles were extracted from a mixture from location 2 which had a fines content (F_2) = 53%, by sieving. Some of the bottom ash particles had a trace of fly ash particles attached to their surfaces. Other particles were entirely consisting of conglomerates of fly ash particles that were

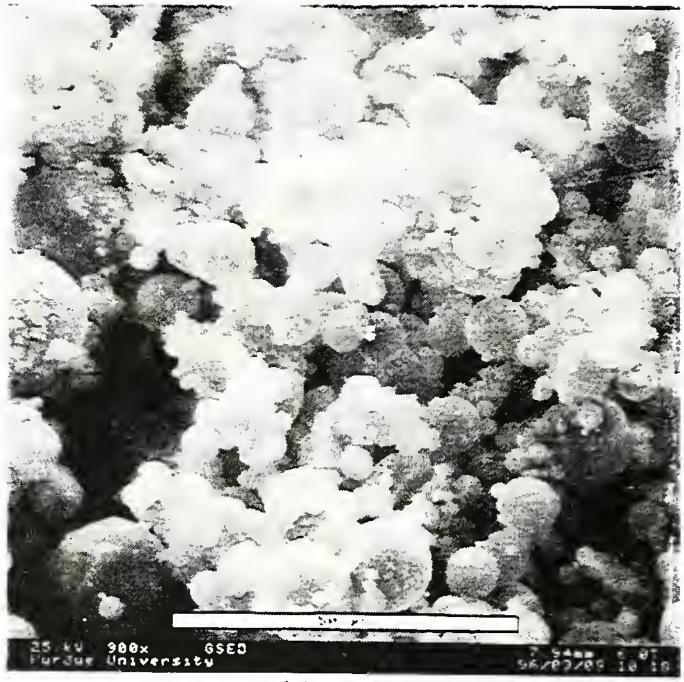
attached together. These particles can be either weakly bonded or strongly cemented together. The weakly bonded particles can be easily broken between the fingers.

Mixtures from Gibson were visually and microscopically examined. Mixtures at F_2= 22, 48, 53, and 74% fines content were examined under the light microscope to study the composition of the particles and the effect of the fly ash particles on masking the surface features of the bottom ash particles. Samples from the explicit mixtures at fly ash contents (F_1) of 10%, 25%, 50%, and 75% were also examined. Figures 4.12 (a,b) display particles in an implicit mixture that had a 22% fines content. Figure 4.12 (a) displays a micrograph of a 0.3 mm bottom ash particle covered with fly ash particles. Figure 4.12(b) displays several particles of bottom ash nearly totally covered with fly ash particles. Figure 4.13 (a,b) display SEM micrographs of particles of ash mixtures from location 1 that passed sieve # 200. The fly ash particles cover bottom ash particles. Some stick-shaped particles appeared in the mixture (possibly some form of calcium composition). Figure 4.14 (a,b) contained a SEM micrograph of a mixture from location 4 (F_2= 48%), Gibson Power Plant. The fly ash particles are covering all bottom ash particles. Agglomerated particles consisting of bonded fly ash particles, either alone or combined with bottom ash particles were found in all size ranges. Some of these particles are weakly bonded and could be broken easily between the fingers. Other particles were strongly bonded and needed tapping with a mallet to break.

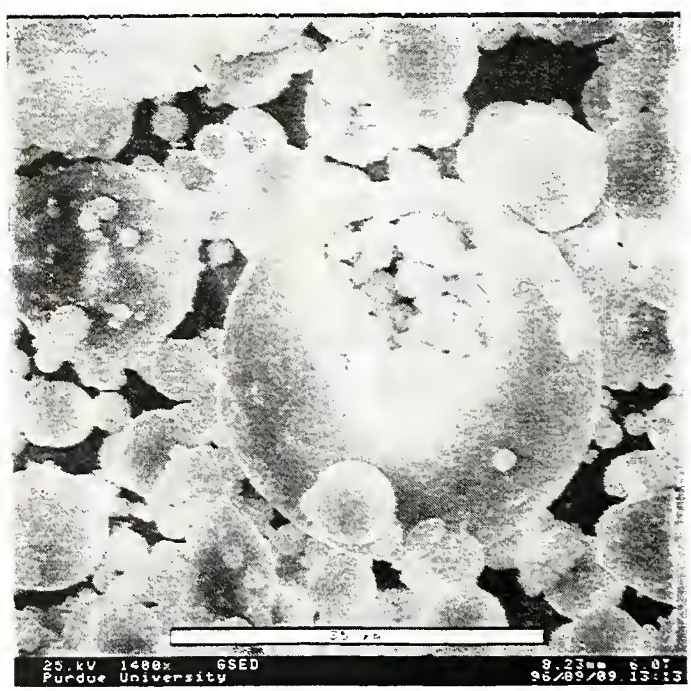
The shape and surface features of Ottawa sand particles, passing #30 (0.50 mm) and retained on #50 (0.3 mm) were also examined. Figure 4.15 displays the sand particles at magnification x30. These sand particles are typically rounded to sub-rounded and their surface is less rough than the bottom ash.

4.3.2 Discussion

The shape, particle size range, and surface features of the bottom ash particles differ from that of the fly ash particles. The bottom ash particles are irregular in shape. In general, more than 90% of the bottom ash particles are greater in size than 0.075 mm. The particles smaller than 0.075 mm were still greater than 0.03 mm. Even at the very fine range of bottom ash particles, the spherical particles in these size ranges appeared to be a minor fraction [see, for example, Figure 4.9(b)]. The surface of a typical bottom ash particle is rough and gritty.



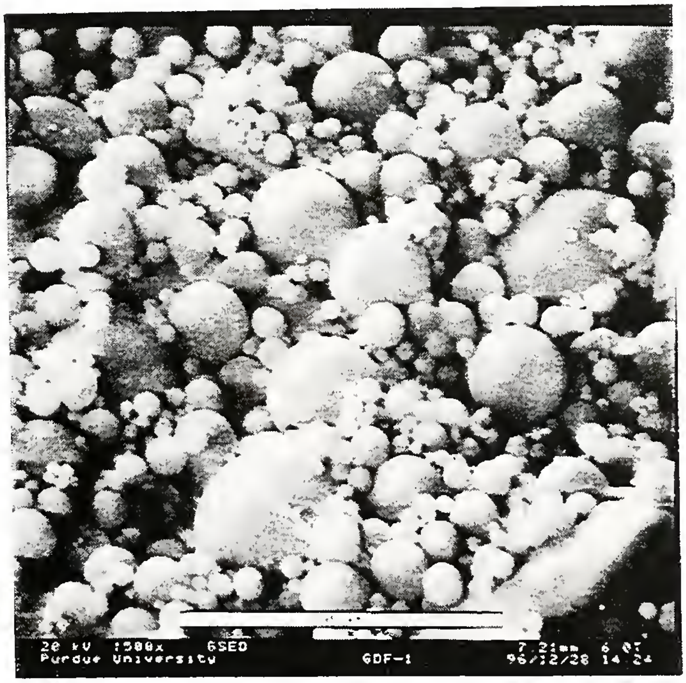
(a)



(b)

Figure 4.7 SEM Micrograph of Class F Fly Ash Particles from the Schahfer Plant: (a) Magnification x900, (b) Magnification x1400.

(a)



(b)

Figure 4.8 SEM Micrograph of Class F Fly Ash Particles from the Gibson Plant: (a)Magnification x900 (b)Magnification x1500.

(a)

(b)

Figure 4.9 SEM Micrograph of Fine Bottom Ash Particles (<0.075 mm) from the Schahfer Plant: (a)Magnification x250 (b)Magnification x400.

(a)

(b)

Figure 4.10 LM Micrograph of Bottom Ash Particles (Schahfer Plant): (a) Retained on # 8 (Magnification x10) (b)Retained on # 16 (Magnification x30) (c)Retained on # 30 (Magnification x25) (d)Retained on Sieve # 50 (Magnification x30), [Cont.]

(c)

(d)

Figure 4.10 [Continued]

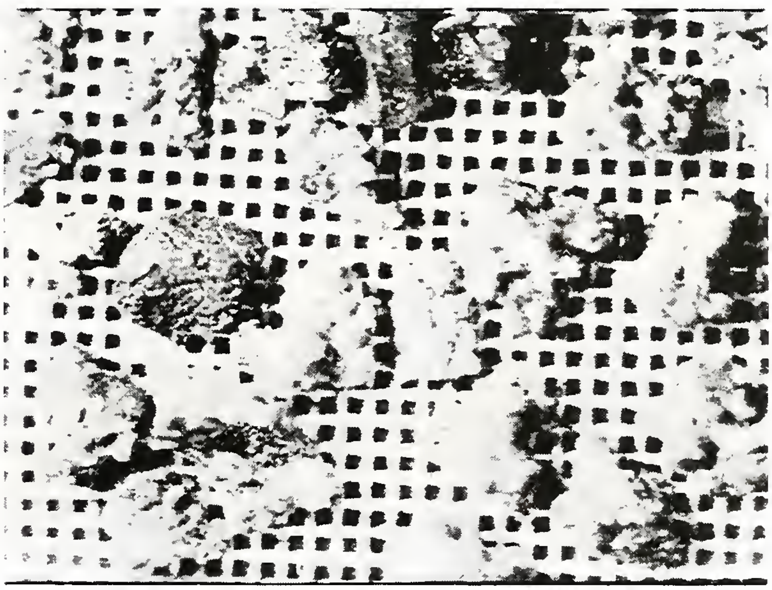
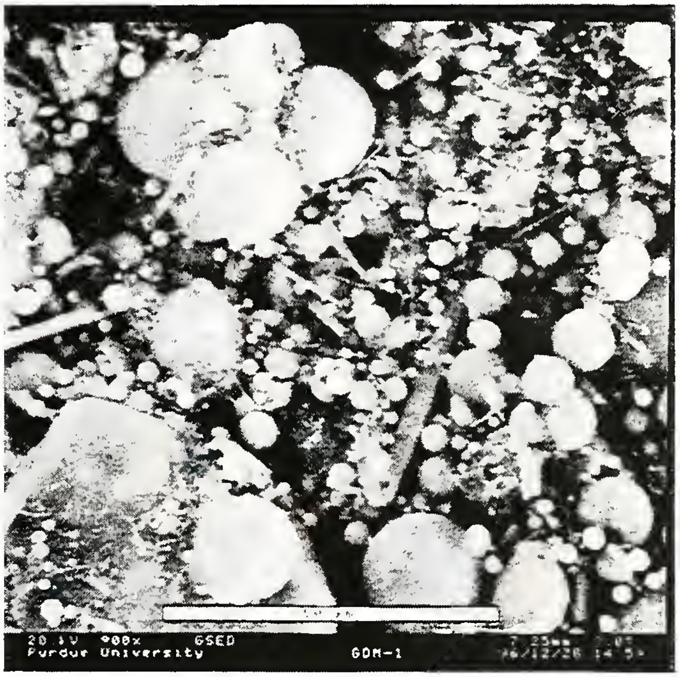


Figure 4.11 LM Micrograph of Bottom Ash from the Gibson Plant (Magnification x30)Passing Sieve # 30 and Retained on Sieve # 50.

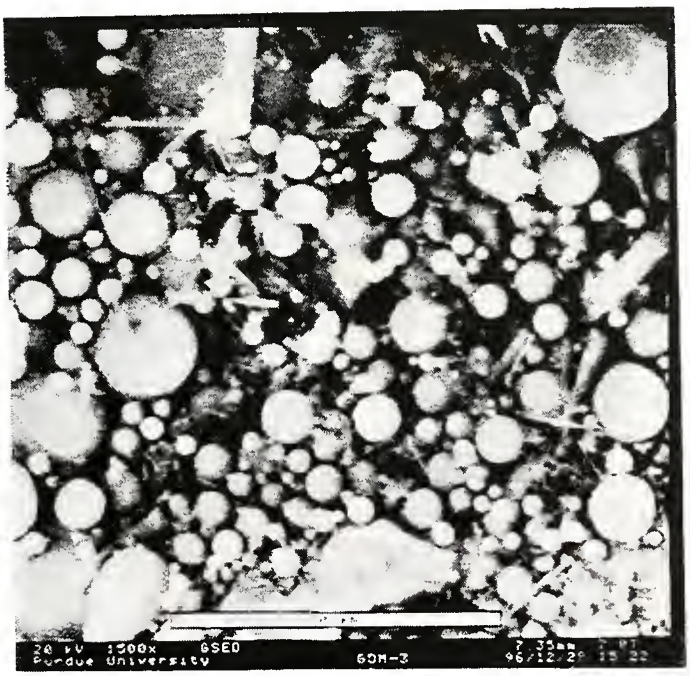
(a)

(b)

Figure 4.12 LM Micrograph of Ash Mixtures from the Gibson Plant With F_2=22%: (a) a Single Bottom Ash Particle Covered With Fly Ash (Magnification x30) (b) Several Particles (Magnification x10)

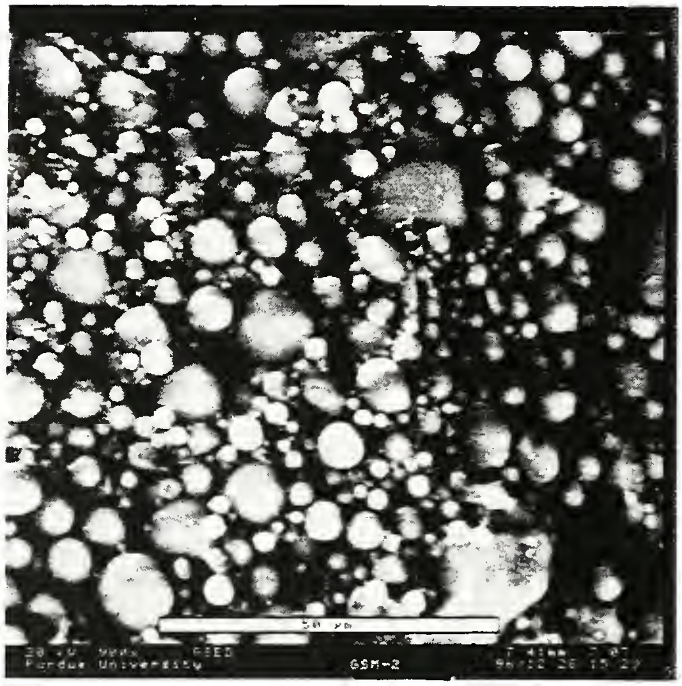


(a)

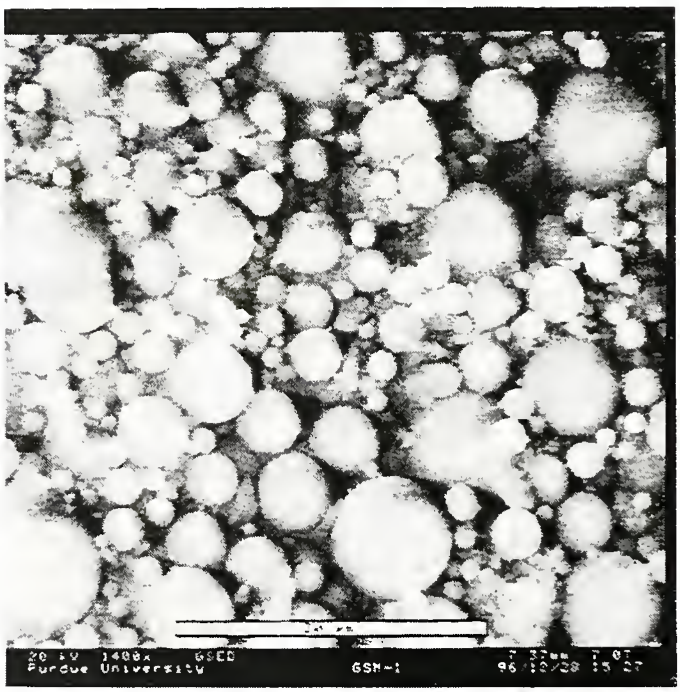


(b)

Figure 4.13 SEM Micrograph of Fines Contained in Fly/Bottom Ash Implicit Mixtures from the Gibson Plant, Location 1 (F_2=22%):
(a) Magnification x900 (b) Magnification x1500.



(a)



(b)

Figure 4.14 SEM Micrograph of Fines Contained in Fly/Bottom Ash Implicit Mixtures from the Gibson Plant, Location 4 (F_2=74%):
(a)Magnification x900 (b)Magnification x1400.

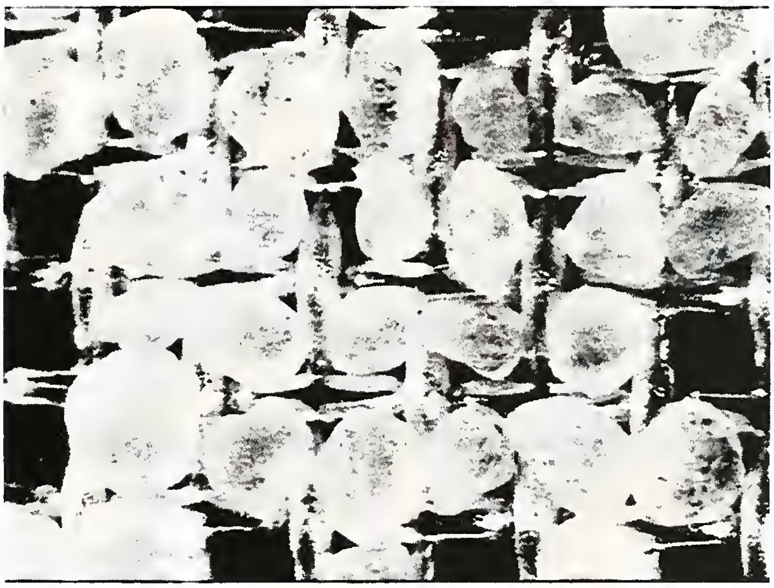


Figure 4.15 LM Micrograph of Ottawa Sand Passing US Sieve #30 and Retained on Sieve# 50 (Magnification x30).

Conversely, the fly ash particles are smaller than 0.075, their shape is spherical, and the particle surface is smooth to very smooth. The surfaces of the samples of fly ash from Gibson had a very smooth surface, smoother than surfaces of Schahfer samples. At $F_1 \leq 10\%$, some of the bottom ash particles are fully covered with fly ash and some are partially covered. At $F_1 \geq 25\%$, the asperities of the bottom ash particles surfaces were covered with the fly ash particles. The thickness of the fly ash layer attached to a bottom ash particle increases as the fly ash content increase.

For the implicit mixtures from Gibson, except for the mixtures from location 1, fly ash particles covered totally the surfaces of bottom ash particles. A percentage of particles composed of agglomerates of bonded fly ash particles alone or combined with particles of bottom ash was found in Gibson mixtures at all sizes. These particles were deposited in loose conditions. Some of them are lightly cemented and some are strongly bonded; as they break they tend to have a volume reduction. The weakly bonded particles may readily break between the thumbs. These particles will be easily broken during compaction. The strongly bonded ones needed tapping with a rubber mallet to break. The particles may break only at elevated shear and volumetric stresses.

4.4 Compaction and Penetration

4.4.1 Compaction Tests

Six explicit mixtures and four implicit mixtures were prepared and tested in compaction (Section 3.3). The fly ash content (F_1) in the explicit mixtures and the percentage passing #200 for the implicit mixtures (F_2) were displayed earlier (Table 3.1 and Table 3.2). The compacted dry unit weight versus the moisture content curves of the explicit mixtures (Schahfer Plant) are displayed in Figures 4.16 (a) and (b). Figure 4.16 (a) displays the compaction curves of the mixtures containing F_1= 0%, 10%, 25%. Figure 4.16 (b) displays the compaction curves of the mixtures F_1= 50%, 75%, and 100%, plus F_1= 25% included for comparison. The results of the compaction of implicit mixtures (Gibson Plant) are displayed in Fig. 4.17. The compacted dry unit weight versus moisture content curves of the implicit mixtures of fines contents F_2= 22, 53, 48, and 74% are displayed.

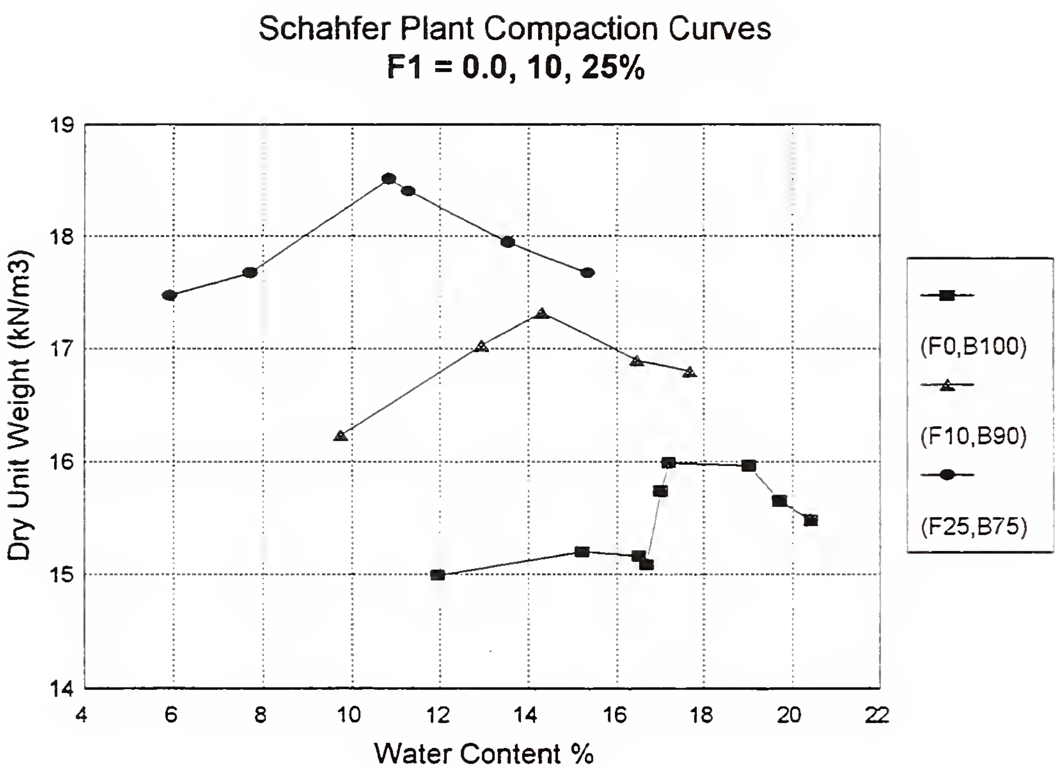
4.4.1.1 Behavior of Bottom Ash

At low moisture contents, part of the compaction effort is expended to overcome the capillary tension between the particles. As the moisture content increases [Fig. 4.16(a)], the effect of the capillary tension is decreased and the compacted dry unit weight increases until a maximum dry unit weight γ_{dmax} is achieved at an optimum moisture content w_{opt} . If the moisture content is increased beyond the optimum point, free water flows out of the ash during compaction. However, when the moisture is retained in the sample, by sealing the base of the compaction mold, the density decreases because of positive pore pressure generation.

4.4.1.2 Behavior of the mixtures

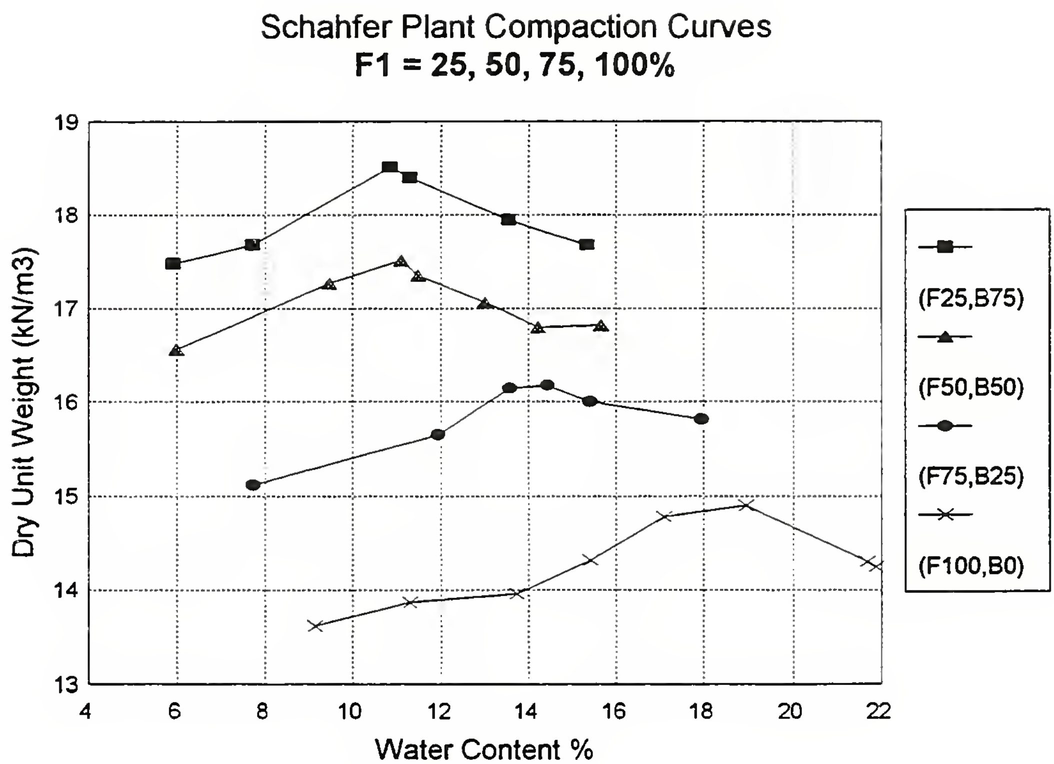
The test results on the explicit mixtures show that as the fly ash content (F_1 %) increases from zero, the optimum moisture content w_{opt} decreases, while the maximum dry unit weight γ_{dmax} increases [Fig. 4.16 (a)]. Initially, in the absence of fly ash, the bottom ash particles are in contact. At low fly ash content ($F_1 = 0$ to 10 %), the fly ash acts as a lubricant, assisting the sliding and rearrangement of the bottom ash into a dense arrangement at lower moisture content and partially filling the inter-particle pores, hence γ_{dmax} increases. Bottom ash particles are still in contact, but their rough surfaces are partially masked. When fly ash content is increased to 25%, the fly ash particles further fill the inter-particle voids and assume a dense arrangement, achieving a maximum γ_{dmax}. Bottom ash particles are either in contact, or contain thin dense layers of fly ash in the middle. Higher fly ash contents separate the bottom ash particles and γ_{dmax} gradually decreases, while w_{opt} increases [Figure 4.16(b)]. At some fly ash contents, all bottom ash particles can be separated, floating in a fly ash matrix. The increase in w_{opt} is needed to release the capillary tension from the greater exposed surface of the fly ash particles. There is an optimum fly ash content at which the densest mixture may be developed. Although, for the explicit mixtures tested, a 25% fly ash content led to the highest γ_{dmax} and the lowest w_{opt}, this is not necessarily the optimum mixture.

Gibson implicit mixtures had fines content (F_2) range of 22% to 74%. As the fines content (F_2 %) increased, w_{opt} increased and γ_{dmax} decreased (Figure 4.17). This indicates that the implicit mixtures from the Gibson plant, except for the sample from location 1, had fines content greater than the optimum. The sample from location 1 had the highest γ_{dmax} and



(a)

Figure 4.16 Compaction Curves of Bottom Ash and Class F Fly Ash Explicit Mixtures of the Schahfer Plant: (a)F_1= 0.0, 10, 25%, (b)F_1= 25, 50, 75, 100%.[Cont.]



(b)

Figure 4.16 [Continued]

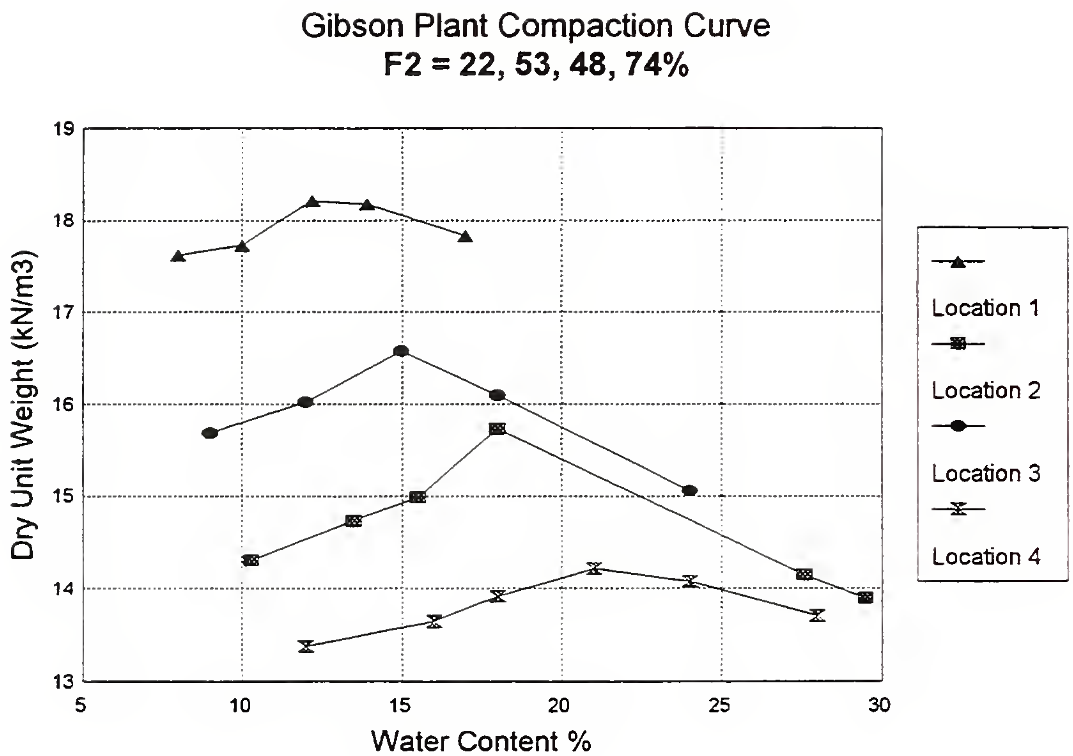


Figure 4.17 Compaction Curves of Bottom Ash and Class F Fly Ash Explicit Mixtures F_2= 22, 53, 48, 74 %.

lowest $w_{opt,}$ and contained the lowest fines content. The grain size distribution, shows that samples with this low fines content normally exist in the vicinity of a discharge point. It can be expected also that as the gradation of the coarse particles become finer, a lesser amount of fines becomes needed to fill the inter-particle voids and reach an optimum fines content.

4.4.2 Penetration tests

Penetration tests were performed on the implicit and explicit mixtures to determine the effect of moisture content on the penetration pressure (Section 3.3). The tests were performed on the compacted samples described by Section 4.5.1. The penetration pressure versus the moisture content, for the explicit mixtures containing F_1 = 25%, 50%, 100%, is displayed in Figure 4.18. The penetration results of the implicit mixtures is displayed in Figure 4.19.

Three types of failure modes were observed as the penetration of the needle advanced. The first type of failure was a general bearing failure (Figure 4.20). The second type of failure is a punching failure, and it occurred on the excessively moist samples (Figure 4. 21). The third type of failure was a punching failure combined with some signs of dilation and cracking. This type occurred at or slightly above the optimum moisture content.

4.4.3 Discussion

The compaction of explicit mixtures of gradually increasing fly ash content display two distinct behaviors. An increase in the dry unit weight and decrease in the optimum moisture contents are observed as the fly ash content increases from zero to a certain fly ash content, after which the dry unit weight decreases and the optimum moisture content increases as the fly ash content increases further to 100%. Townsend (1972) reported similar behavior for sand and silt mixtures. If only one mixture exists in the site, the choice of the moisture range for compaction can be a simple process. The difficulty may arise when a fill is composed of several mixtures and all are compacted at the same moisture range, using a single energy level. Different responses will be achieved from the different mixtures. For example a moisture range of 16 to 18% seems appropriate for compacting $F_1 \geq 95\%$ or $F_1 \leq 5\%$, but is too wet for compacting most of the mixtures. Conversely, compacting at a

moisture range from 9 to 11% seems to be reasonable for the mixtures where F_I= 25% to 75%, but 9 to 11% would be too dry for compacting the fly ash. Excessively dry compaction can lead to reduction in γ_{dmax} , and perhaps dusting. Increasing the compaction effort may increase the dry unit weight, but there are technical and economic limitations to increasing the compaction effort. There is also a potential for over-compaction. Excessively wet compaction can also lead to reduction of γ_{dmax}, in addition to the potential for softening and pumping. Increasing the compaction effort does not improve the compaction in this case.

Penetration resistance can provide guidance for the upper level of the moisture range to use in the compaction. The penetration tests indicate that moisture content ranges in excess of the optimum moisture content may not be suitable for compaction of the mixtures. The surface penetration is a form of bearing capacity failure. The bearing capacity increases as the shear strength increases. Compacted mixtures are normally in a partially saturated condition. Below the optimum moisture content, as the moisture content increases, the added component of strength due to capillary tension is gradually reduced, while the dry unit weight increases. As the moisture content increases beyond the optimum point, the reduction of the dry unit weight in addition to the loss of capillary tension lead to the significant loss of the resistance to penetration. When a compacted mixture becomes saturated, the added component of strength due to capillary tension diminishes. The shearing resistance becomes due to cohesionless strength, mainly derived from frictional and dilatational behaviors, as will be discussed in the next chapter.

A range of 3 to 5% dry of optimum moisture content may be most appropriate for compaction. Even for free-draining bottom ash, there is an expected level of moisture content beyond which the moisture will flow through the ash pores. Unless effective drainage is provided out of the fill, this excess water may remain within the fill. If a clay liner exists below the ash, it may swell and possibly soften, if the ash lifts do not provide enough counter pressure to prevent the swelling. This effect can be more important in the early stages of construction.

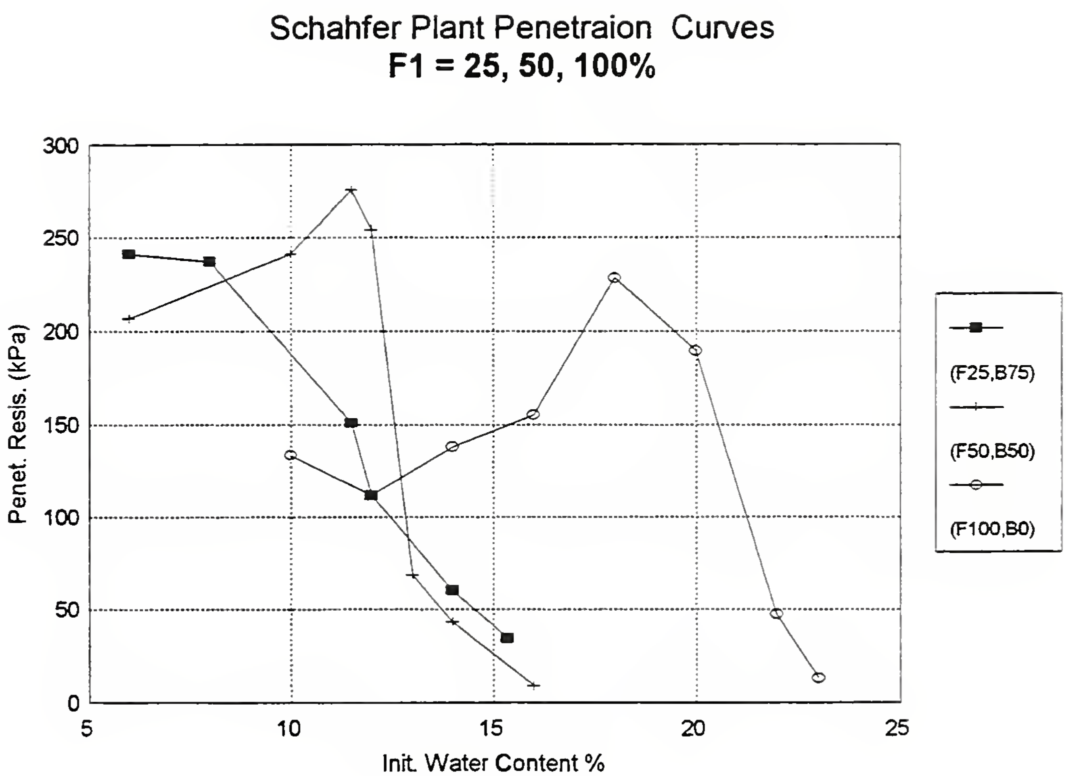


Figure 4.18 Penetration Curves of Compacted Explicit Mixtures from Schahfer Bottom Ash and Class F fly ash (F_1 = 25%, 50%, 100%).

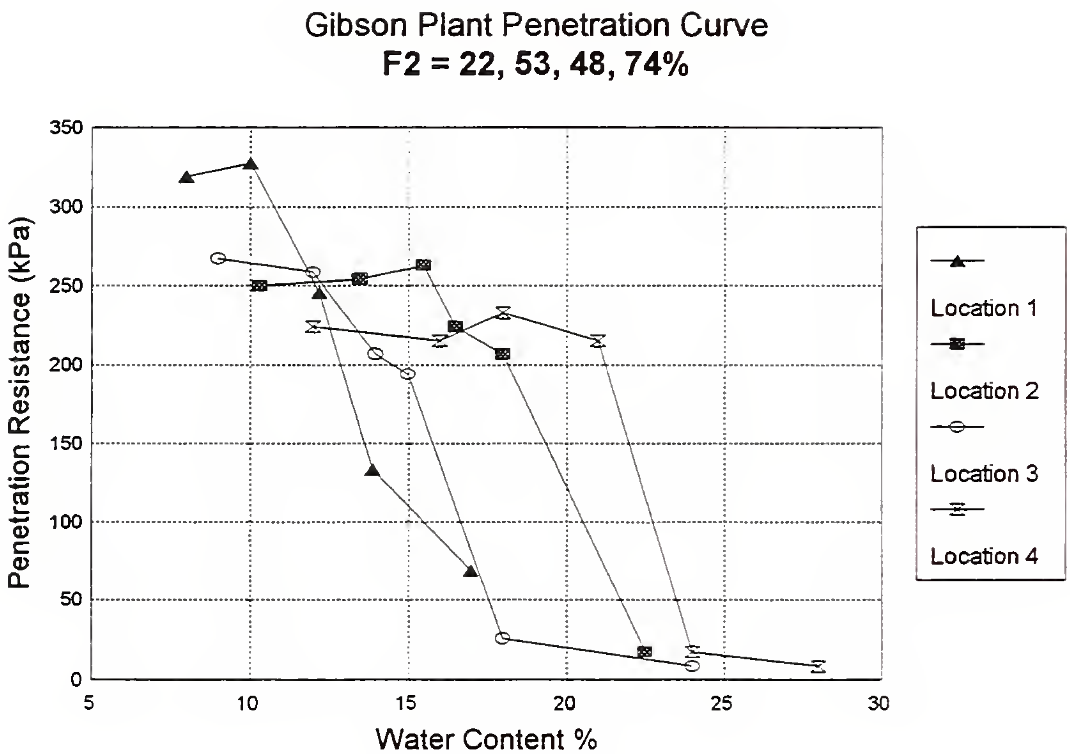


Figure 4.19 Penetration Curves of Compacted Implicit Mixtures from Gibson Bottom Ash and Class F fly ash (F_2= 22%, 53%, 48%, 74%).

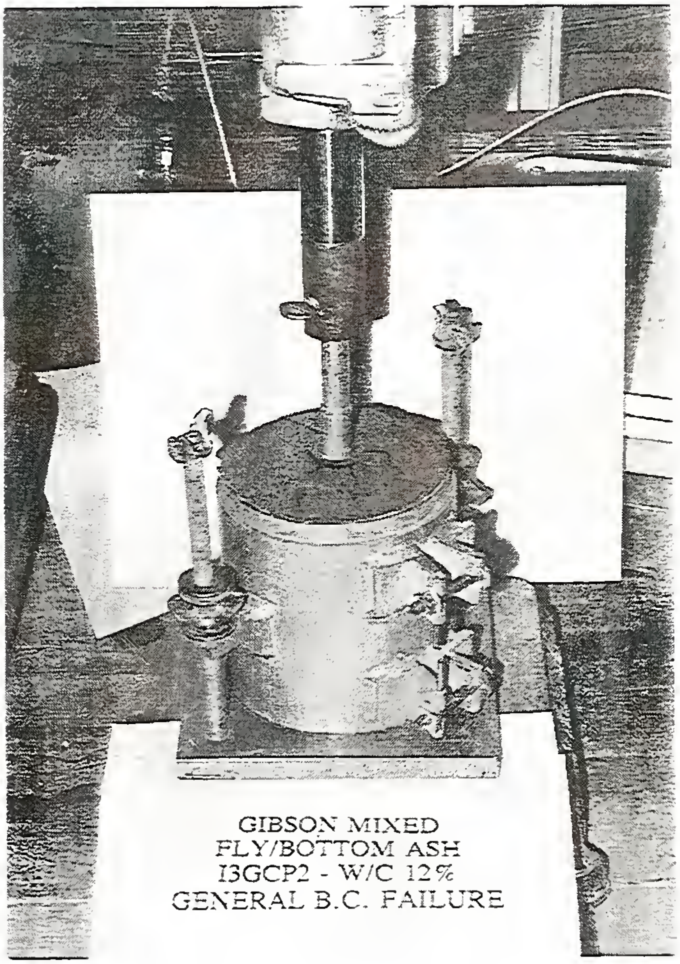


Figure 4.20 Surface Penetration of a Sample Compacted on the Dry Side of Optimum Moisture Content (General Bearing Capacity Failure due to a Stiff Behavior).

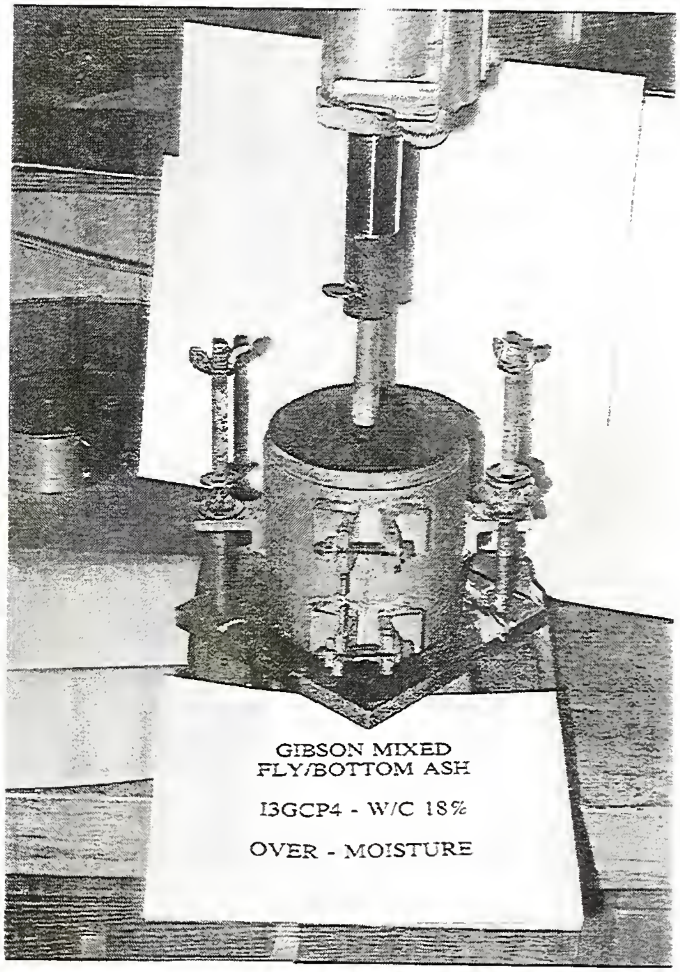


Figure 4.21 Surface Penetration of a Sample Compacted on the Wet Side of Optimum Moisture Content (Punching Shear Failure Due to Soft Behavior).

4.5 Maximum and Minimum Density

4.5.1 Test Results

The maximum and minimum density values were obtained for samples of explicit mixtures of F_1 = 0%, 10%, and 25%. The experimental procedure is described in Section 3.4. Table 4.1 displays the values of the maximum and minimum density for the mixtures tested. The mixture with F_1= 50% was also tested, but, significant dusting occurred during the vibration and, hence, the results were not accurate. A comparison between the maximum densities achieved by vibration and ASTM D 698 procedures, shows that the vibration procedure provides practically similar dry unit weight at F_1 = 25%. A similar behavior was displayed by mixtures of sands and silts (Townsend 1972). A mixture of well graded sand with fines content of 23% was compacted using vibration (in dry conditions) and using ASTM D 698 (at optimum moisture content); the max dry unit weight provided by both methods was essentially the same. It was stated that the maximum and minimum density depend on the gradation and the percentage of fines. Normally one expects that more fines can fill voids of a uniform sand than a well graded sand.

4.5.2 Discussion

Using the vibratory table, the maximum dry unit weight increases as the fly ash content increases from zero. The fly ash particles gradually fill the inter-particle voids and lead to a dry unit weight increase. A comparison between the maximum densities achieved by vibration and ASTM D 698 procedures, shows that the vibration procedure provides slightly higher dry unit weight at F_1 = 25%. At F_1 = 0 and 10%, the vibration provided higher dry unit weights than ASTM D 698. The vibration becomes increasingly more effective as the fly ash content decreased.

At high fly ash contents (50% and higher), the vibration was not suitable for either dry or saturated mixtures. Dry samples emitted dust and led to unreliable results due to the loss of disturbed fines. Saturated samples of such fines content liquefy due to positive pore pressure generation from the vibration. The maximum and minimum density values are necessary to compute the relative density of a compacted granular material. The relative

Table 4.1 Maximum and Minimum Density Tests on Explicit Mixtures (From Schahfer Plant)

Mixture	Fly Ash Content F_1 %	Max. Dry Density (Vibration) (kN/m^3)	Min. Dry Density (kN/m^3)
TXA1	0.0	16.38	13.01
TXA2	10	17.53	14.36
TXA3	25	18.40	15.17
TXA4	50	17.88	14.56

density can then be used as an alternative to the relative compaction for controlling the compaction. As the fines content increase in a mixture, the accuracy of the procedures for obtaining the maximum and minimum densities becomes questionable. Selig and Ladd (1972) evaluated the relative density and its applications and discussed the method's limitations, sources of error, and advantages of the method. They concluded that the relative density can be a suitable method for control of granular materials compaction, however, they referred the choice of using either the relative density or alternative method to the project engineer. They emphasized the considerable care that needs to be practiced during the maximum and minimum density determinations in addition to the field density measurements.

4.6 Summary

The gradation of bottom ash in disposal sites contained sizes that ranged mostly from fine sand to fine gravel. The majority of the samples tested had a gradation similar to well graded sands. The fly ash particle sizes range from fine sand to fine silt. The majority were in the ranges of silt sizes. The bottom ash gradation depends on the method of disposal, distance from disposal points, environmental aspects, and man-made changes. For implicit mixtures that are co-ponded, the proportions of generation and the rates of discharge of the different types also affect the gradation. For explicit mixtures, the fly ash to bottom ash ratios can be specified. The mixtures are thus composed of the individual bottom ash and fly ash particles. Implicit mixtures, however, consist of the individual fly ash and bottom ash particles plus agglomerates of bonded particles of fly ash, either alone or combined with bottom ash particles. The percent of particles smaller than 0.075 mm (# 200 US sieve) is used to describe the amount of fines in the mixture.

Interaction between the different types of particles affect the behavior of the mixtures in compaction and penetration. The maximum compacted dry unit weight increases gradually until it reaches a maximum value as the fines content increase in the mixture from zero to an optimum value. The increase in the maximum dry unit weight is associated with a decrease in the optimum moisture content. As the fines content increases further in the mixtures, the maximum dry unit weight decreases. The decrease in the maximum dry unit weight is associated with an increase in the optimum moisture content of the mixtures. Implicit mixtures

with fines content greater than the optimum are expected to experience a decrease in the maximum dry unit weight and an increase in the optimum moisture content. For a mixture, the penetration resistance decreases significantly as the moisture content increases more than the optimum. This indicates that compaction on the dry side of the optimum is more appropriate. As the mixtures become excessively dry, however, dusting can occur and compaction become increasingly difficult due to the effect of capillary tension between the particles. In the field, the range should be determined based on the range of existing mixtures and the required level of compaction. Controlling the compaction using the relative density can be less suitable as the fines content increase in the mixture. The testing method using ASTM D 698 has two advantages: it can be used for testing mixtures with a wide range of moisture contents and fines content, and it significantly minimizes or eliminates dusting. On the other hand, the method however may not simulate the compaction method used in the site.

CHAPTER 5
SHEAR STRENGTH AND VOLUMETRIC BEHAVIOR OF COAL ASH MIXTURES

5.1 Overview

In order to study the behavior of compacted mixtures of different proportions of fly and bottom ash in shear strength, isotropically consolidated, drained (CID) triaxial compression tests were conducted. This chapter presents the results and discussion of the triaxial experimental program. The compressible behavior of the mixtures is examined. The effects of changes in the mixtures composition and the confining pressure on the volume change and the rate of consolidation are discussed. The results of the shear tests using the triaxial procedures are extensively discussed and analyzed in the following sequence: for each mixture at a relative compaction R, the deviatoric stress and volumetric strain were plotted versus the axial strain at three levels of confining pressure σ'_3. The stress paths of the tests are displayed. The mobilized angle of shearing resistance is plotted against the axial strain. A discussion and analysis of the behavior of each mixture follows.

To further focus and analyze the results, the peak angles for the different mixtures were plotted against the fly ash content F_1 in the case of the explicit mixtures and against the fines contents F_2 in the case of the implicit mixtures. The plots were generated at a relative compactions R= 90% and 95%. The volumetric behavior during shear is discussed, including the compressive and dilative behavior of the mixtures. The use of the Bolton's (1986) correlation for predicting the difference between the peak angles and the critical state angles based upon the mean effective stress and the relative density is attempted. Correlation parameters Q and R are evaluated for the explicit mixtures that are rich in bottom ash and the results are compared with those obtained for typical sands.

Although the subjects presented in this chapter were constructed with their application to embankments as the primary objective, the results and discussions introduced in this chapter can be extended to a wider range of stability and stress-strain problems involving coal ash mixtures. The experimental program included selecting five explicit mixtures from Schahfer power plant (F_1= 0, 25, 50, 75, 100%) and three implicit mixtures from Gibson Power plant (F_1= 22, 53, 74%) to be tested. Six samples were formed from each mixture and divided into two groups, three samples each. The first group of samples was compacted at a relative compaction R= 95%, and the second group, at R=90%. Three levels of effective confining pressures were used per group (Section 3.5). The composition, size, compaction ratio R, and confining pressures σ'_3 of each sample were presented earlier (Tables 3.3 and 3.4).

5.2 Compressibility

5.2.1 Test Results

The samples for triaxial testing were compacted, then placed in the cell under an initial effective confining pressure of 20 kPa. The samples were then saturated using back pressure saturation while maintaining the effective confining pressure σ'_3 at 20 kPa. They were then consolidated using σ'_3 as displayed in Tables 3.3 and 3.4. The volume change (measured by the burette readings) due to consolidation was recorded against the time. The change in volume (measured by the burette reading) was then plotted against the logarithm of time to define the time and volume change at 100% consolidation. Figures 5.1 and 5.2 display change in volume [displayed in terms of (1-dv/v), where, v is the initial volume before consolidation and dv is the change in volume] with respect to time for samples TXB1Hc (F_2= 22%, R= 95%, σ'_3= 200 kPa), TXB4Hc (F_2= 74%, R= 95%, σ'_3= 200 kPa) and TXB4Lc (F_2= 74%, R= 90%, σ'_3= 200 kPa). The time for 100% consolidation was estimated from these plots to range approximately from 0.15 to 2 minutes. These represent the range of times recorded for primary consolidation at the high stress level (σ'_3= 200 kPa). The time for consolidation decreases as σ'_3 decreases. Using the volume

change versus the square root of time gave practically the same results. The time for consolidation increases with increasing fines content and decreases with increasing compaction ratio R.

The volume change (dv) at the end of consolidation was also determined. As the effective consolidation pressure increased on the samples, the volume change increased. In order to demonstrate the effect of the compaction level on the compressibility of mixtures containing similar fines content (F_2), the quantity (1-dv/v) at the end of consolidation was plotted versus the effective confining pressure for implicit mixtures. The mixtures were compacted to a relative compaction (R) of 95% and 90%. Figure 5.3 [(a), (b), and (c)] displays the effect of R on the volume change for implicit mixtures of similar fines content (F_2). The volume change due to consolidation decreases as the relative compaction R% increases. The dense compacted mixtures displayed a percentage volume change of less than 0.5%. The loose compacted mixtures of high fines contents (50% and greater) display relatively higher volume changes than the mixtures of low fines content. As the fines content decreases to 22%, the volume change is relatively less.

5.2.2 Discussion

The compaction process changes the ash mixtures in ways that can be considered similar to the effects of preconsolidation. The volume reduction in the case of compaction, however, occurs in the volume of the air voids at a constant moisture content. The smaller the compaction ratio (R%) is, the smaller the reduction in voids (air voids), and the greater the volume change due to consolidation (as the sample becomes loaded after compaction), especially at high consolidation pressures as the effect of prestress due to compaction becomes exceeded. The implicit mixtures compacted at R= 90% displayed volumetric strains ϵ_v ranging from 0.7 % (for F_2 = 22%) to 2.25% (for F_2 = 74%) due to isotropic consolidation pressure equal to 200 kPa.

As the relative compaction increases (R= 95%), the stiffness of the ash mixture increases, the voids ratio decreases, and the volume change due to consolidation decreases, as long as the consolidation pressure is less than the prestress due to compaction. The time

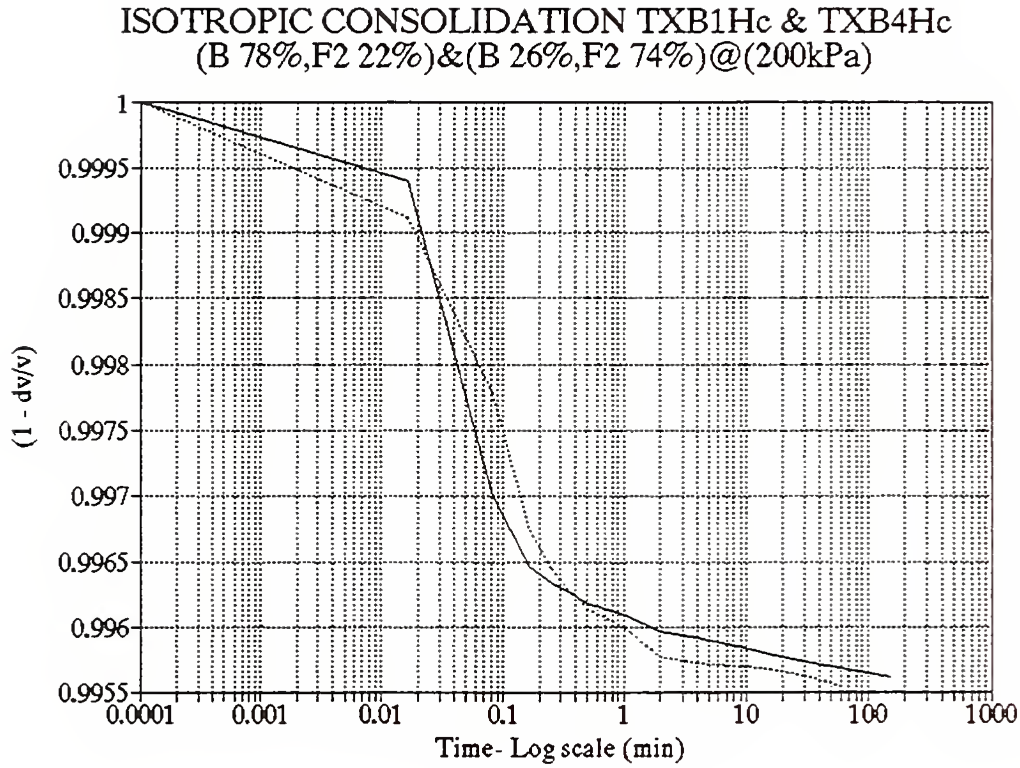


Figure 5.1 Isotropic Consolidation of Implicit Mixtures Compacted at R=95%, Consolidation Pressure of 200 kPa, and Fines Contents F_2= 22%, 74% [(1/dv/v) vs. Time)].

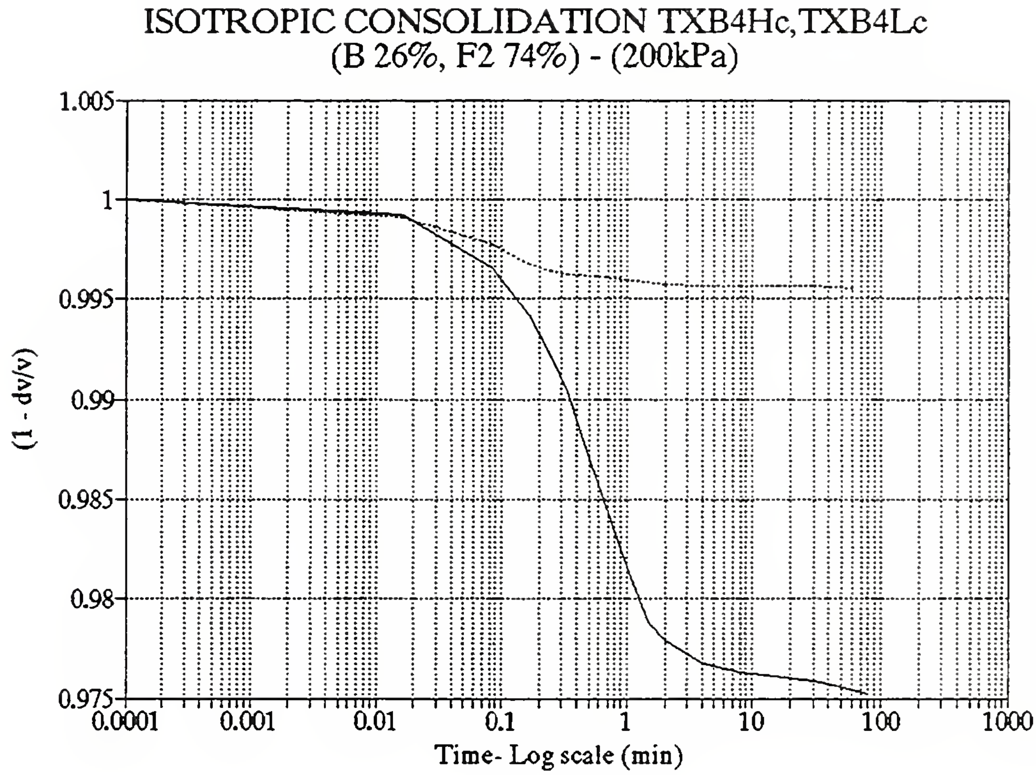


Figure 5.2 Isotropic Consolidation of Implicit Mixtures With Fines Content F_2=74%, Consolidation Pressure of 200 kPa, and Compacted at R=95%, 90% [(1/dv/v) vs. Time)].

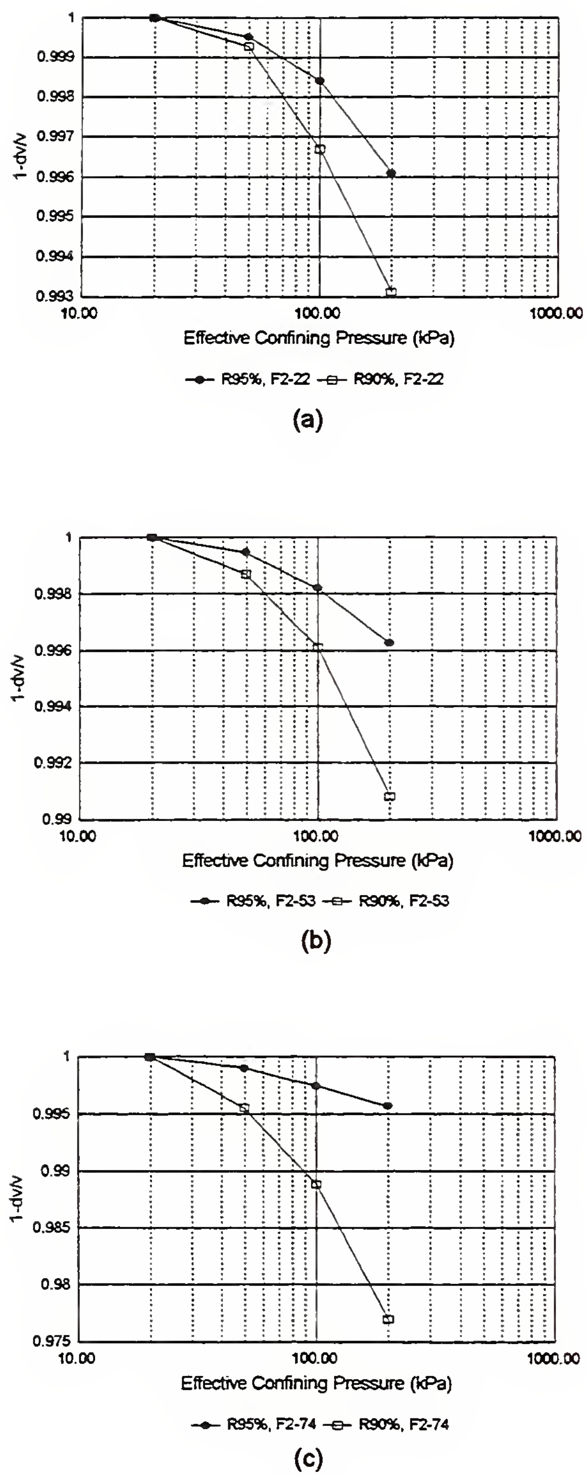


Figure 5.3 Isotropic Consolidation for Implicit Mixtures.

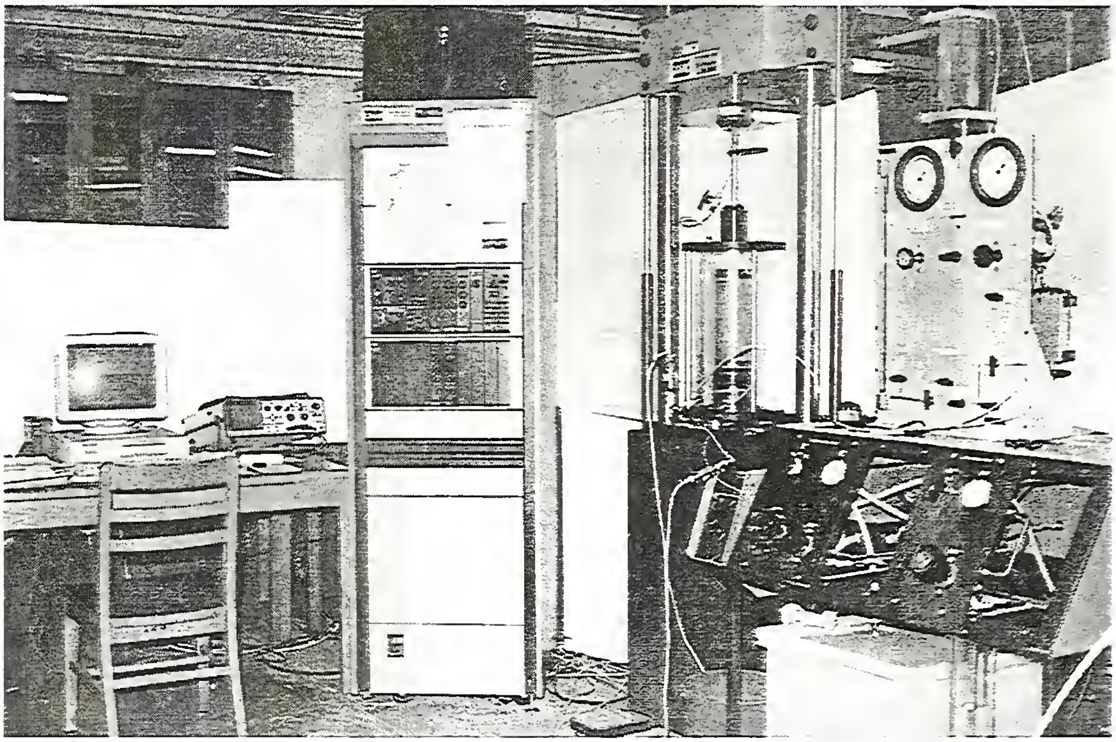
for consolidation also decreases as the strains become mostly elastic. Due to an isotropic consolidation pressure of 200 kPa, ϵ_v was in the range from 0.4% (for F_2 = 22%) to 0.5% (for F_2= 74%). The difference between the two ranges of ϵ_v (at R= 90% and 95%) illustrates the significance of changing the relative compaction level. A secondary mechanism, due to the collapse of weakly bonded particles, may be considered. As the relative compaction increases, most of the weakly bonded agglomerates of particles are broken and do not contribute further to the volume changes that occur during the consolidation.

As the fines content increases, the permeability of the mixtures decreases and the time for volume change increases, at the same compaction level. The mixture stiffness decreases as the fines content increases for mixtures compacted at the same relative compaction (R). This leads to increasing the magnitude of the volumetric strain and the time required to complete the volume change as the fines content increases.

5.3 Shear Behavior

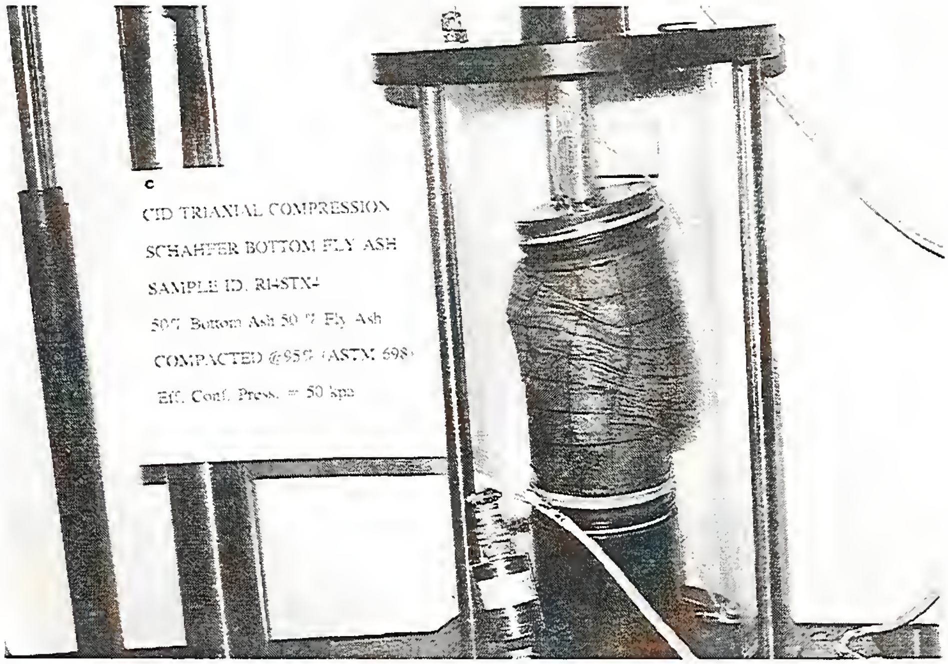
5.3.1 Introduction

The samples were sheared in the triaxial apparatus under strain controlled drained conditions. As a sample was deforming axially at a constant rate, the vertical load was automatically measured and recorded simultaneously with the axial deformation. The volume change due to the deviatoric stress was also monitored and recorded. The deviatoric stress $\sigma_d = \sigma'_1 - \sigma'_3$ was calculated and plotted against the axial strain ϵ_a. The mobilized angles of shearing resistance, $\phi'_m = \sin^{-1}(\sigma'_1 - \sigma'_3/\sigma'_1 + \sigma'_3)$ were calculated. Figure 5.4(a) displays a 4 in. sample before shearing and the MTS testing system. As the axial strain increases, the sample deforms gradually until failure occurs. Figures 5.4 (b) and (c) display the two common failure patterns observed for the ash mixtures. Clearly identifiable failure plane occurs for the dilatant stiff samples. The bulging pattern was commonly observed for the contractive loose samples. Some samples displayed more complex patterns, that is, a composition of those two patterns.



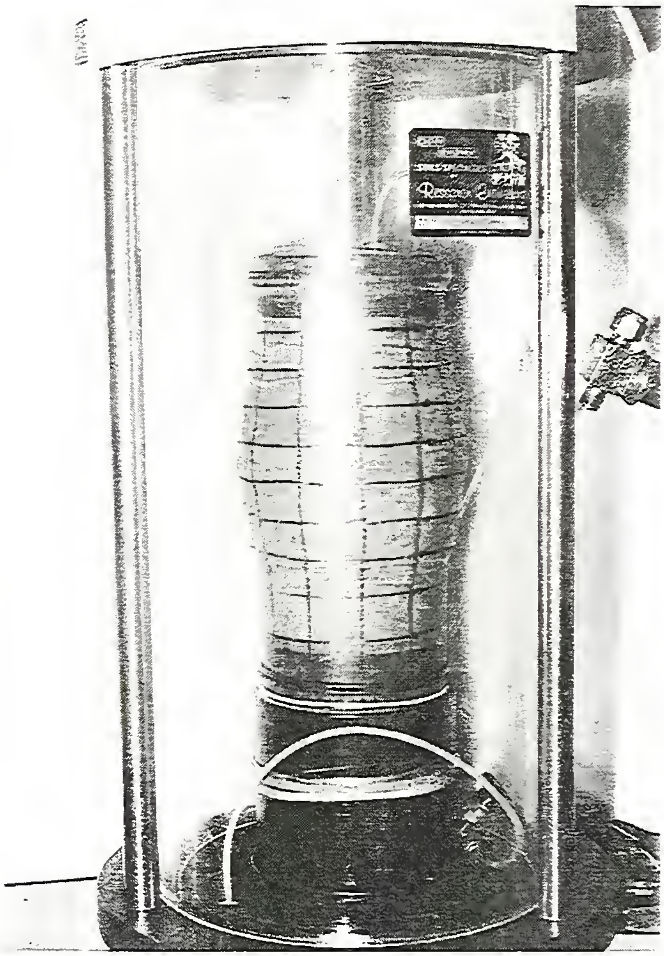
(a)

Figure 5.4 Triaxial Samples (a)Intact Sample Mounted on MTS Soil Mechanics Test System (b) Failed Sample (Failure on a Plane) (c) Failed Sample (Bulging Failure). [Continued]



(b)

Figure 5.4 [Continued]



(c)

Figure 5.4 [Continued]

5.3.2 Behavior of Explicit Mixtures

5.3.2.1 Test Results

Figures 5.5 (a) displays the deviatoric stress versus the axial strain of bottom ash samples (F_1= 0) compacted at R= 95% and tested at the effective confining pressure σ'_3 levels (a=50 kPa, b=100 kPa, c=200kPa). Similarly, Figure 5.5 (b) displays the volumetric stress versus the axial strain. Figure 5.5 (c) displays the stress path (q-p') diagram. Figure 5.5 (d) displays the mobilized angle of shearing resistance versus the axial strain. Subsequently, the mixtures compacted at 95% are displayed in Figures 5.6, 5.7 5.8, and 5.9 for F_1= 25%, 50%, 75%, and 100%, respectively. Similarly, at R=90% and F_1= 0.0, the results are displayed on Figure 5.10 (a, b, c, and d). The triaxial test results of the explicit mixtures compacted at 90% for F_1 = 25, 50, 75, and 100%, are displayed in Figures 5.11, 5.12, 5.13, and 5.14, respectively.

5.3.2.2 Discussion

a- Explicit Mixtures Compacted at R= 95%

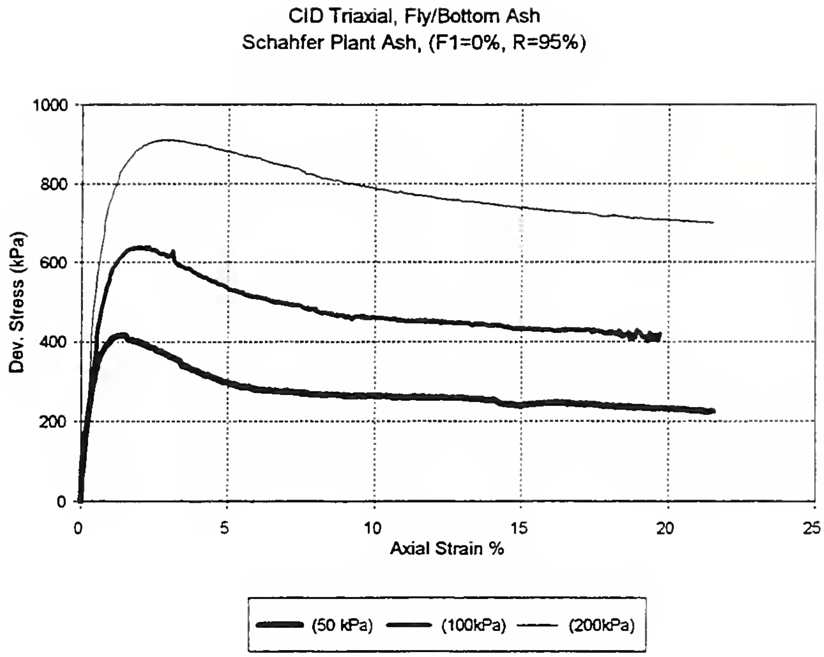
The bottom ash (F_1= 0.0) is a well graded granular material. The shearing resistance of the bottom ash increases as the density increases. For the dense samples (R=95%), the deviatoric stress increases to a peak, then drops with increasing the axial strain. The increase in deviatoric stress is associated with a slight initial volumetric contraction, followed by a gradually increasing rate of volume expansion (dilation). The peak strength occurs when the ratio ($d\epsilon_v/d\epsilon_a$) reaches a maximum value [Figures 5.5 (a,b)]. The post-peak reduction in deviatoric stress is associated with a decreased rate of dilation until shear at a constant volume occurs at a critical state. Dilation is gradually decreased as the confining pressure σ'_3 increases. Since these tests are drained tests, the stress path (q-p') diagram displays a straight line inclined at 45° from the horizontal [Figure 5.5 (c)]. The value of q increases gradually as p' increases until a maximum q is reached then p' and q decrease until a critical state is observed. At a constant confining pressure σ'_3, as the axial strain increases from zero, the mobilized angle of shearing resistance increases to a maximum (ϕ'_{max}) then gradually decreases until it reaches a critical value (ϕ'_{crit}) [Figure

5.5 (d)]. At the same level of axial strain, the mobilized angles of shearing resistance decrease as the confining pressure increases.

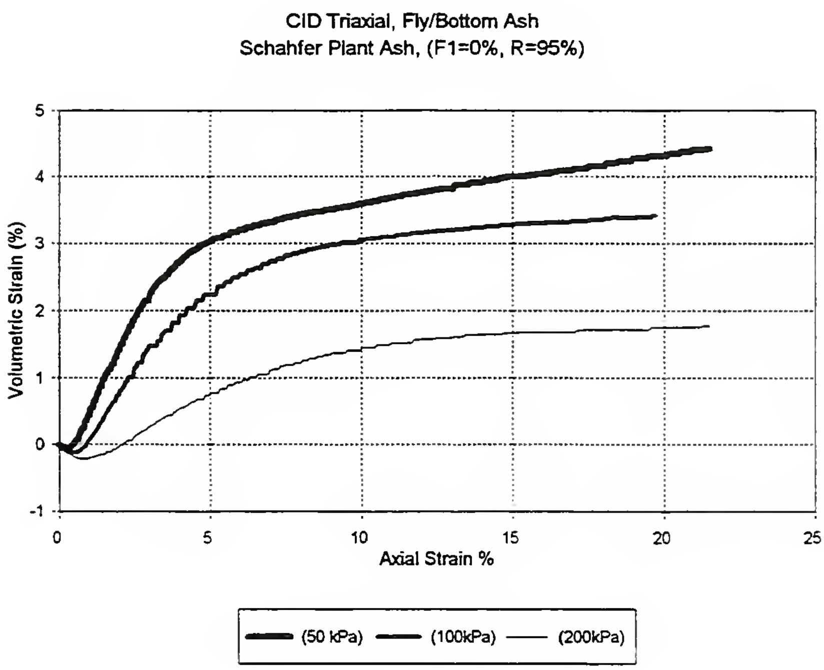
As the fly ash content (F_1) increases to 25% (TXA3H a,b,c), the samples display a dilative behavior at the three levels of σ'_3 [Figures 5.6(a,b)]. The magnitudes of dilation observed for the mixture where F_1 = 25% in terms of the volumetric strain were less than those observed for bottom ash (F_1 = 0%). At this level of fly ash content, and relative compaction (R= 95%) the fly ash particles are masking the bottom ash particles and filling the inter-particle voids. However, denser arrangements are still possible. Thus the dilative volumetric strain required for mobilizing the maximum deviatoric stress, becomes less than the bottom ash alone. The maximum rate of dilation $(d\epsilon_v/d\epsilon_a)_{max}$ and the maximum dilation decrease as the confining pressure increases. The axial strains required for the mobilization of the maximum deviatoric stress were practically the same as those observed in the case of the bottom ash. Due to the reduction in strength after peak strength is reached, the stress paths display a reduction in p' and q after reaching a peak value. At the same levels of axial strain, the mobilized angle decreases as the confining pressure σ'_3 increases [Figure 5.6 (d)].

As F_1 increases from 25% to 50% (TXA4H a,b,c), the peak deviatoric stresses decrease significantly [Figure 5.7 (a)]. Only a slight post peak reduction is displayed by the samples as the axial strains increase. The volumetric strain behavior becomes contractive at all levels of confining stresses [Figure 5.7 (b)]. Although a very slight tendency for dilation was displayed by the sample tested at σ'_3= 50 kPa. The contractive behavior was greater as σ'_3 was increased to 200 kPa. The magnitude of q increases to a maximum then decreases very slightly [Figure 5.7 (c)]. At the same level of axial strain, the mobilized angle decreases as the confining pressure σ'_3 increases [Figure 5.7 (d)]. The maximum shearing resistance was mobilized at an axial strain range of ϵ_a between 0.5% and 2%.

As F_1 increases from 50% to 75% (TXA5H a,b,c) , the deviatoric stresses change slightly and the sample response becomes stiffer [Figure 5.8 (a)]. The efficiency of packing increases and a dilative behavior is observed at σ'_3= 50 kPa. Tendencies for

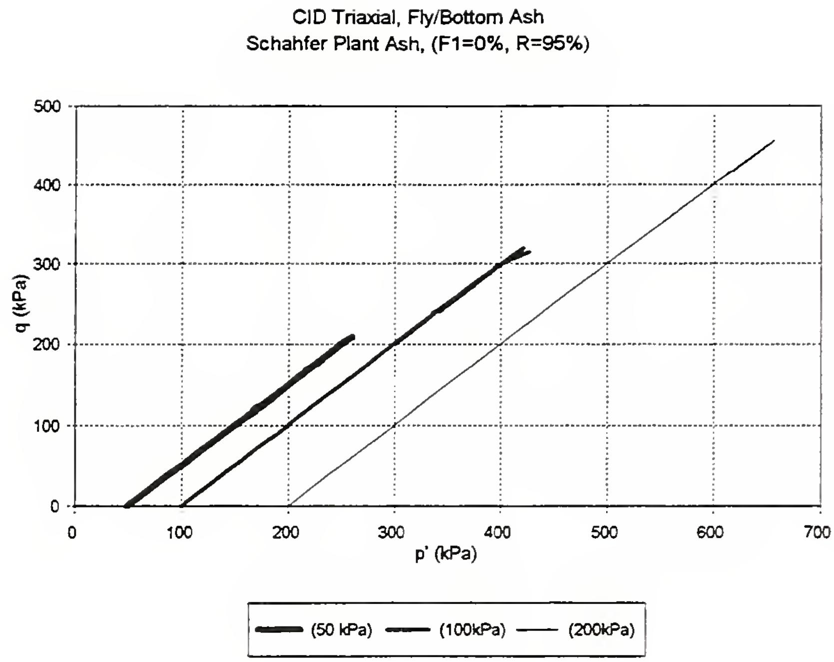


(a)



(b)

Figure 5.5 CID Triaxial Tests on Bottom Ash (F_1=0.0), Compacted at R= 95% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs. Axial strain. [Continued]



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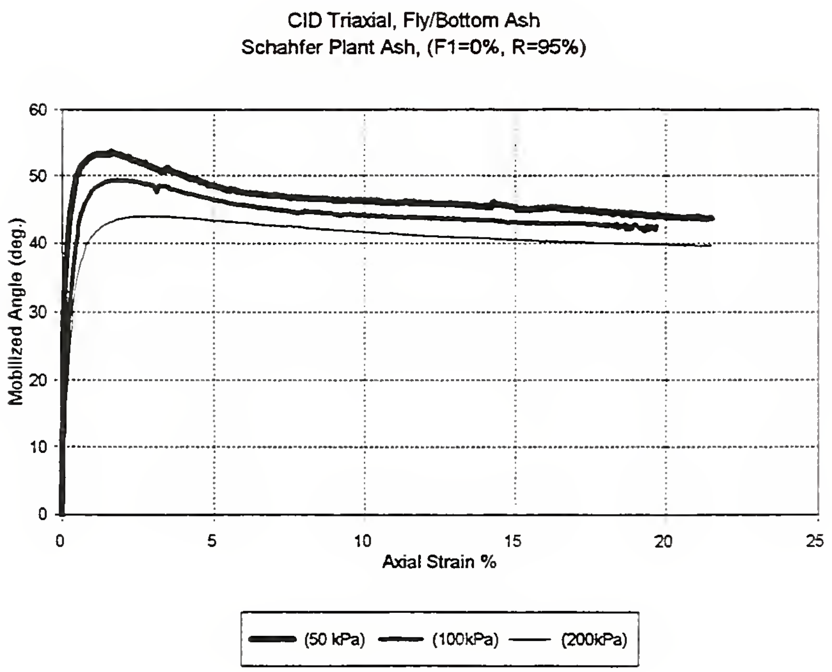
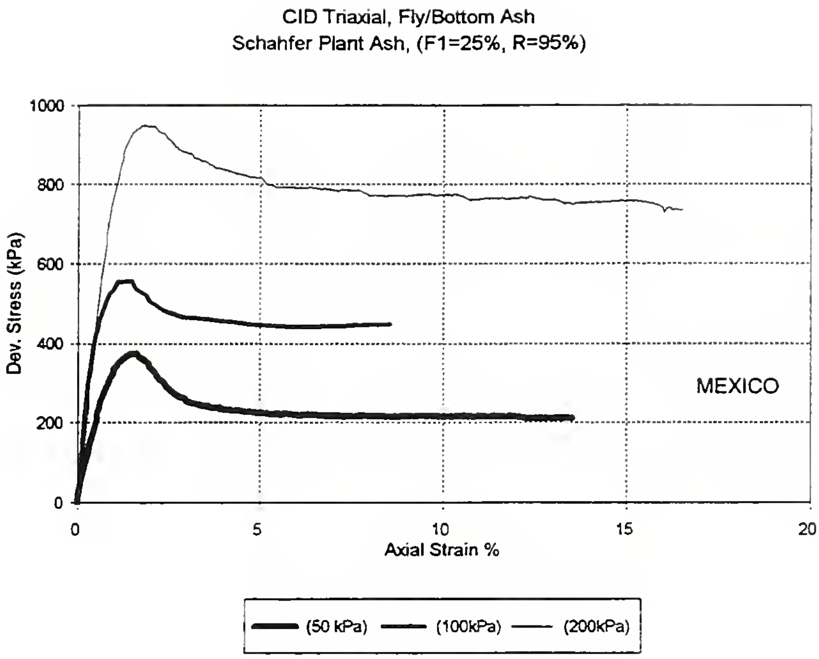
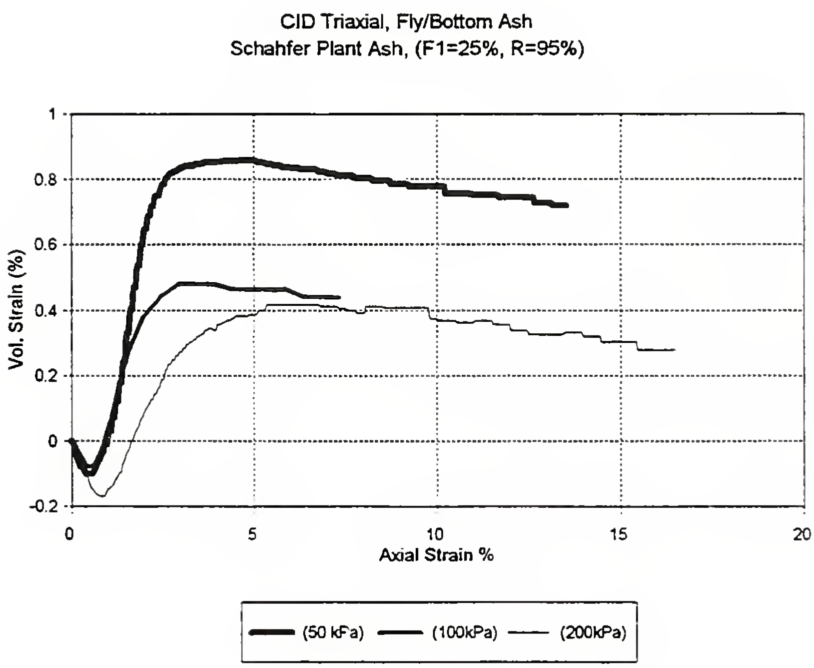


(d)

Figure 5.5 [continued]

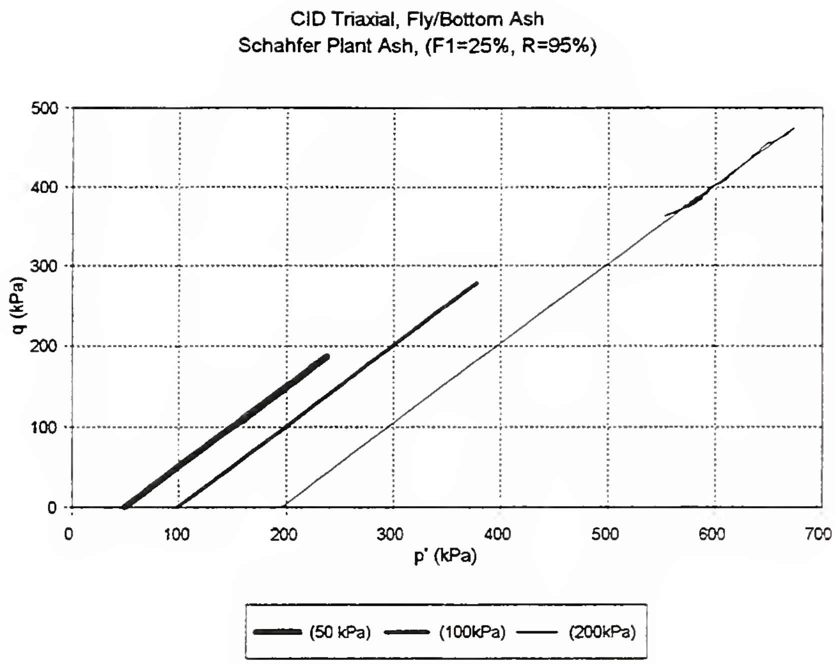


(a)

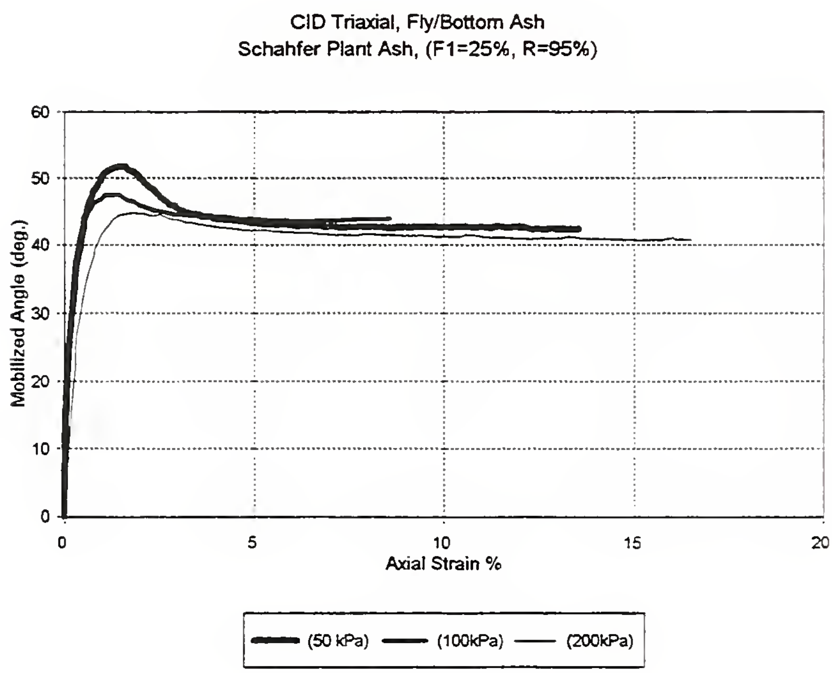


(b)

Figure 5.6 CID Triaxial Tests on Explicit Mixtures (F_1 = 25%)Compacted at R= 95% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs. Axial Strain. [Continued]

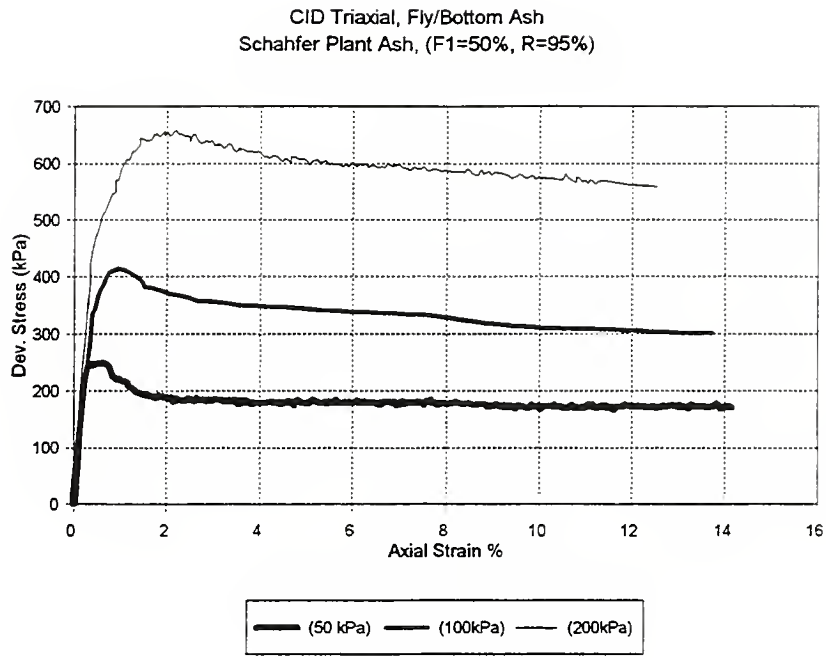


(c)

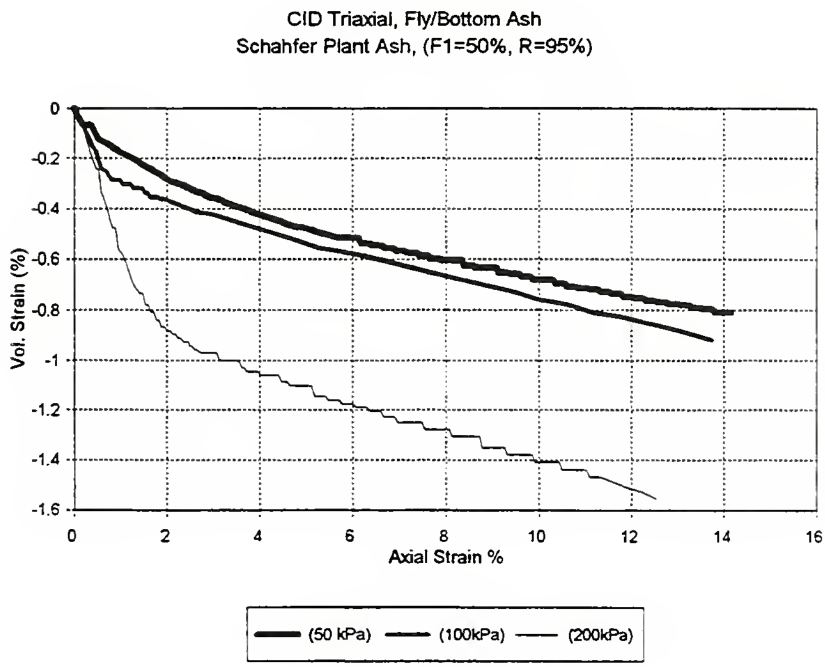


(d)

Figure 5.6 [Continued]

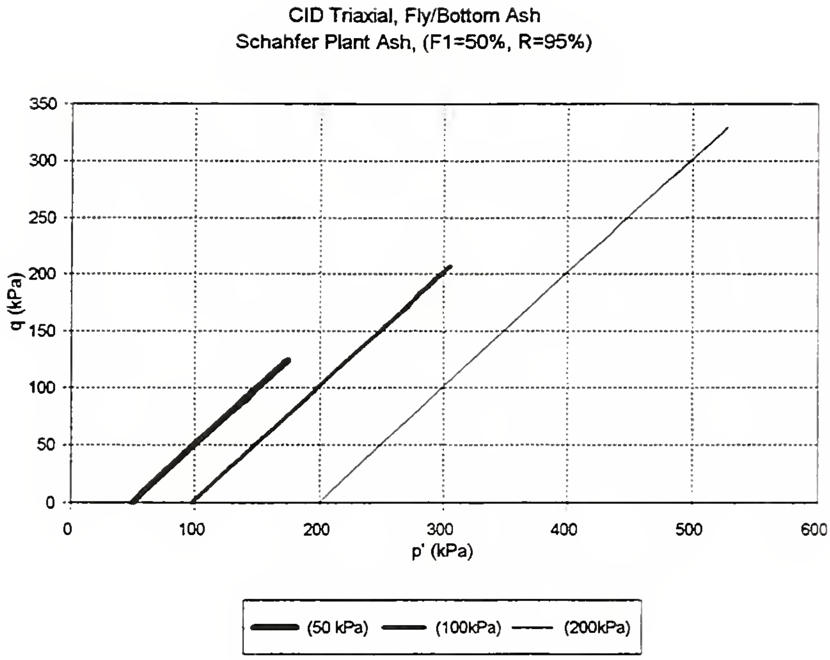


(a)



(b)

Figure 5.7 CID Triaxial Tests on Explicit Mixtures (F_1 = 50%)Compacted at R = 95% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs. Axial Strain. [Continued]



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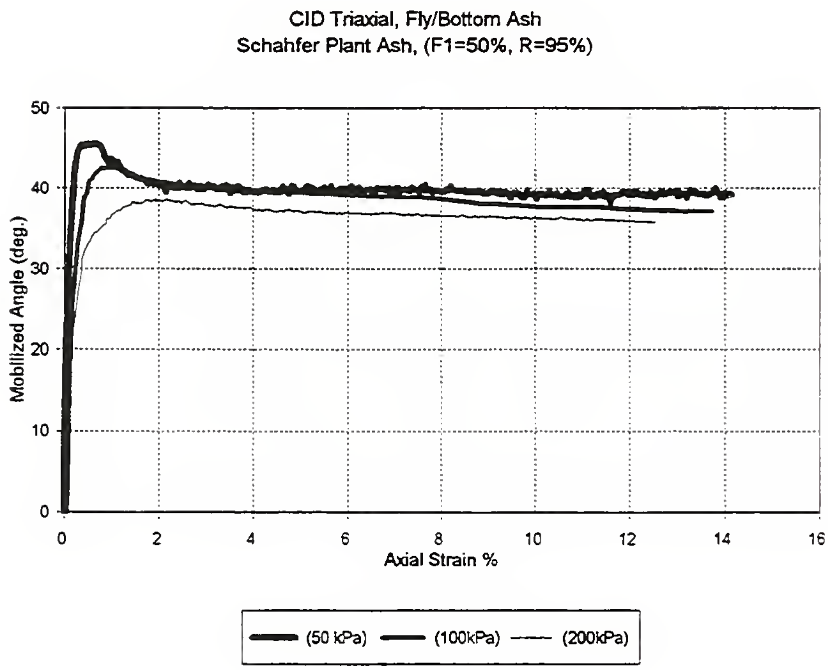

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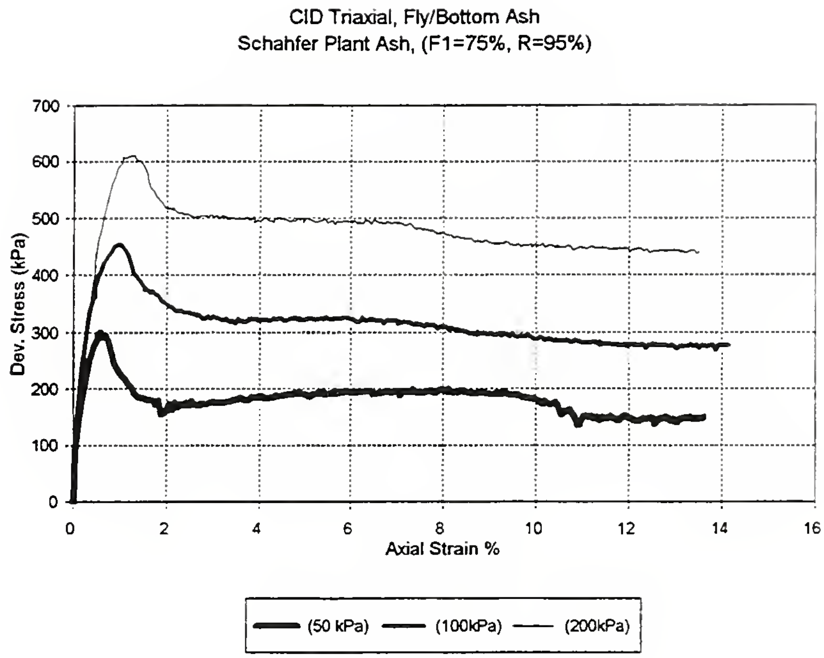
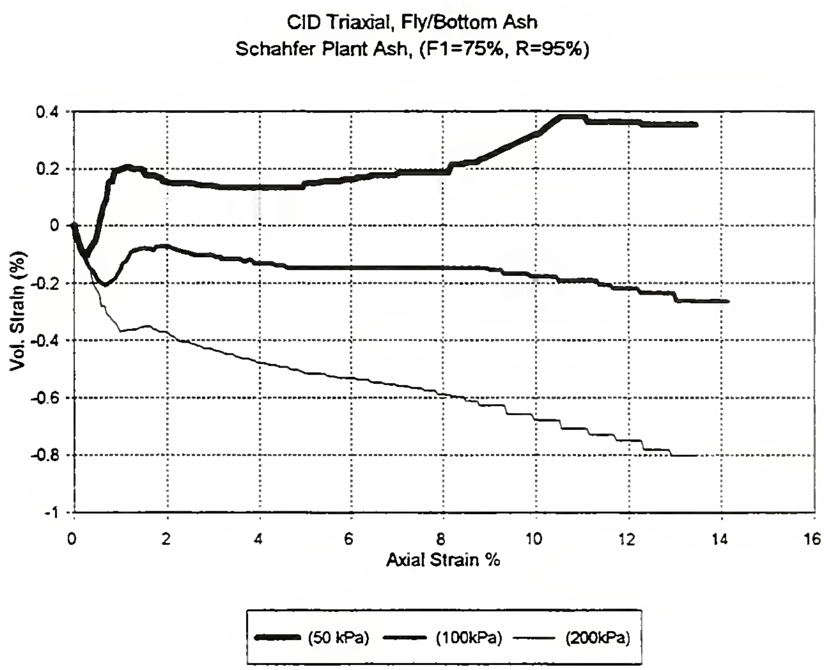
Figure 5.7 [Continued]

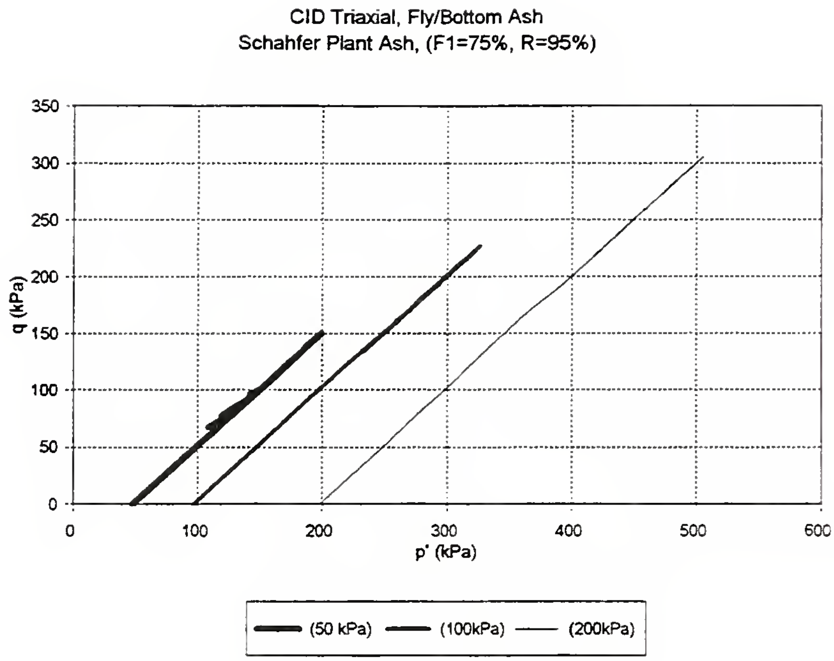


(a)



(b)

Figure 5.8 CID Triaxial Tests on Explicit Mixtures (F_1 = 75%)Compacted at R= 95% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs.Axial Strain. [Continued]



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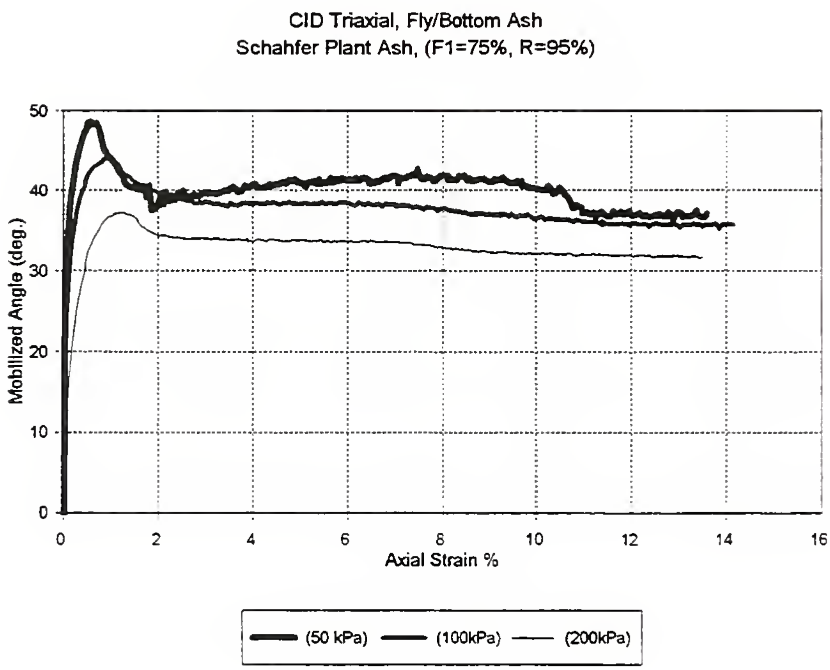
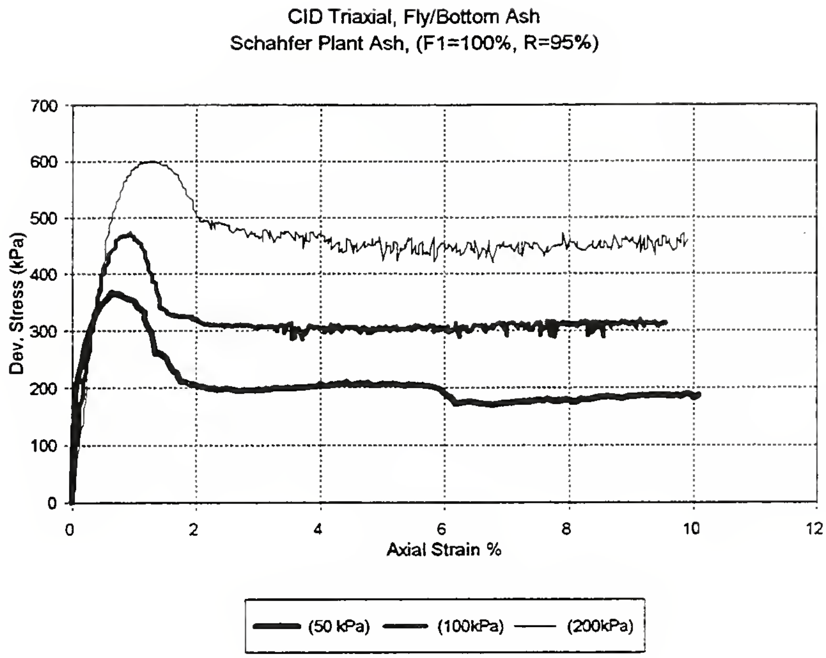
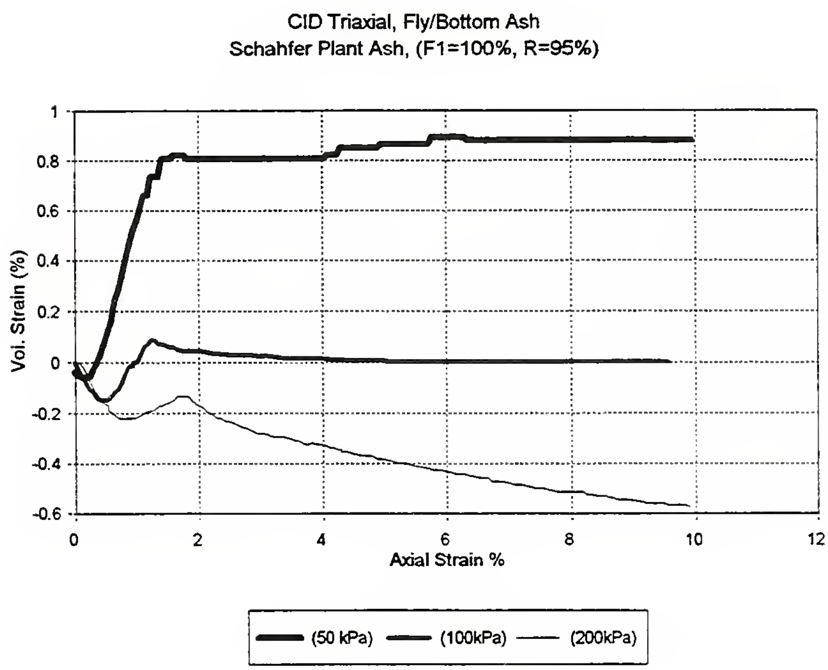


(d)

Figure 5.8 [Continued]

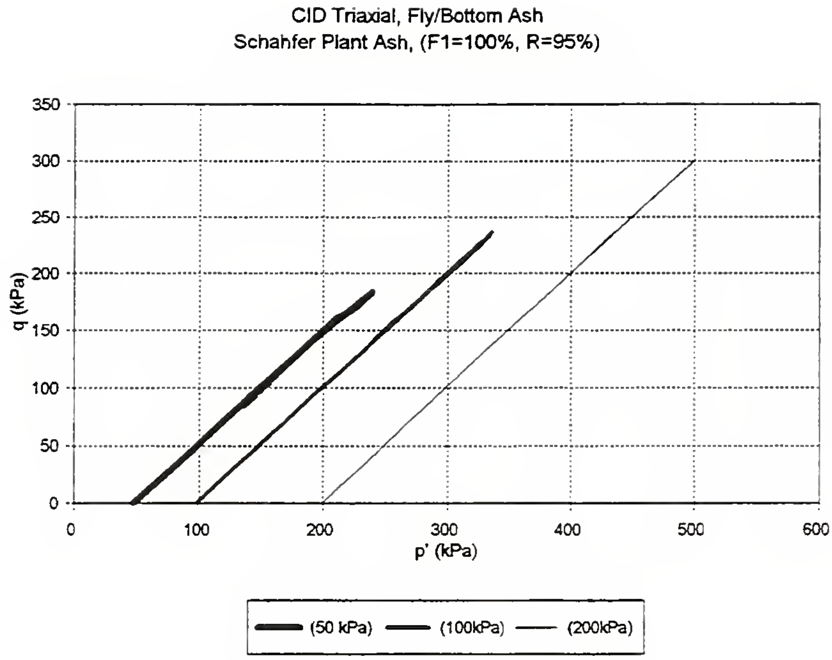


(a)



(b)

Figure 5.9 CID Triaxial Tests on Explicit Mixtures (F_1 = 100%)Compacted at R= 95% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs. Axial Strain.[Continued]



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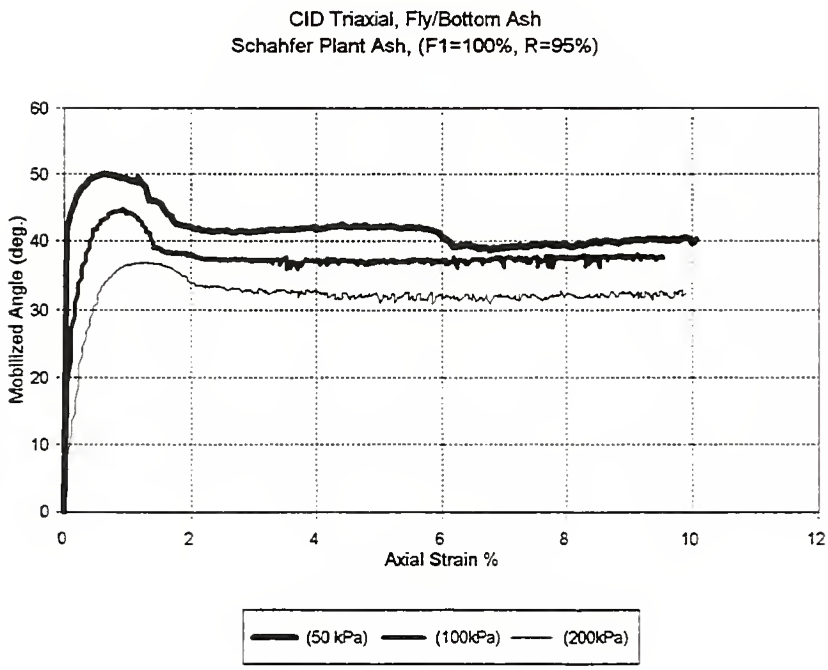


(d)

Figure 5.9 [Continued]

dilation are also observed for σ'_3 = 100 and 200 kPa [Figure 5.8 (b)]. The stress path diagrams display increase in p' and q to peak values followed by a decrease until shearing at a critical state takes place [Figure 5.8(c)]. The mobilized angles of shearing resistance decrease as the effective confining pressure increases [Figure 5.8(d)]. The peak strengths are mobilized at relatively small strains. The stresses also drop to their ultimate values at relatively small strains (ϵ_a= 2%).

As F_1 increases to 100% (TXA6H a,b,c), the samples display a very slight change in the deviatoric stresses reached. [Figure 5.9(a)]. The deviatoric stress increases to a maximum then decreases until it reaches a constant value as the axial strain increases from zero. There is also a slight increase in the dilative behavior. Dilation is observed for the samples tested at σ'_3= 50 and 100 kPa [Figure 5.9(b)]. A tendency for dilation is also observed for σ'_3 = 200 kPa. Accordingly, the magnitudes of q and p' increase to maximum values then decrease [Figure 5.9(c)]. The mobilized angles of shearing resistance increase gradually to a peak then decrease slightly as the axial strains increase [Figure 5.9(d)]. As the effective confining pressure increases, the mobilized angles decrease at the same axial strain level. It can be observed for F_1= 75% and 100% that the mobilized strength angles change slightly as the axial strains increase beyond 2%.

b- Explicit Mixtures Compacted at R= 90%

A significant decrease in shear strength occurs due to the reduction of the relative compaction from 95% (TXA1H a,b,c) to 90% (TXA1L a,b,c). Although the bottom ash samples (F_1= 0) compacted at R=90% display a dilative behavior when tested at σ'_3= 50 kPa and 100 kPa, the maximum deviatoric stresses are significantly less in comparison to those achieved at R= 95% [Figures 5.10 (a,b)]. As the effective confining pressure increases to σ'_3= 200 kPa, (sample TXA1Lc), the volumetric strains are contractive as the axial strains increase from zero. The magnitudes of maximum volume increase for the samples tested at σ'_3= 50kPa and 100 kPa are approximately 50% of those observed at R= 95%. The reduction in the deviatoric stress and the angles of shearing resistance past the peaks are more gradual than those compacted at R= 95%. As displayed in the stress

path diagram, p' and q increase to peak values then decrease [Figures 5.10 (c)]. The mobilized angle of shearing resistance decreases as the confining pressure increases. The change in the mobilized angles is greater at small axial strains than that at larger strains [Figures 5.10 (d)].

As F_1 increases to 25% (TXA1L a,b,c) a significant change occurs in the strength and volumetric behavior at this level of compaction (R=90%). The maximum deviatoric stresses are reduced [Figures 5.11 (a)], and the volumetric strains become contractive at all three levels of confining pressure (σ'_3= 50, 100, and 150 kPa). The magnitude of compressive volumetric strains increase as σ'_3 increases [Figures 5.11 (b)]. The values of p' and q increase gradually to a maximum [Figure 5.11(c)]. The mobilized angle of shearing resistance increases gradually as the axial strains increase [Figure 5.11(d)]. At the same axial strain level, as the confining pressure increases the mobilized angle decreases. The maximum shearing resistance angles are mobilized at higher strains as σ'_3 increases.

As F_1 further increases to 50%, the maximum deviatoric stresses continue to decrease significantly [Figures 5.12 (a)]. The volumetric strains remain contractive at the three levels of confining pressure (σ'_3= 50, 100, and 200 kPa) [Figure 5.12(b)]. The magnitude of compressive volumetric strains increase as σ'_3 increases. The sample TXA4Lb (σ'_3= 100 kPa, F_1= 50%) was slightly undercompacted. This explains why the sample was almost as contractive as TXA4Lc (σ'_3= 200 kPa, F_1 = 50%). The samples display values of p' and q that increase gradually to a maximum [Figure 5.12(c)]. The mobilized angle of shearing resistance increases gradually as the axial strains increase [Figure 5.12(d)]. At the same axial strain level, as the confining pressure increases the mobilized angle decreases. Axial strains of approximately 5% are necessary to mobilize maximum shearing resistance angles as low as 30° to 32°. The mobilized angles decrease as σ'_3 increases.

As F_1 increases to 75% [TXA5H (a, b, and c)] and 100% [TXA6H (a, b, and c)], minor changes are observed in the maximum deviatoric stresses at this level of compaction, [Figures 5.13 and 5.14]. Sample TXA4Lc (F_1=75%) was slightly over-

compacted and that led to stiffening the sample slightly and reduced the volumetric strains. The volumetric strains remain contractive, however. At the same R and F_1 values, a sample compacted at R= 90% would become more contractive (greater ϵ_v) than a sample compacted at R value slightly greater than 90%. Since the sample at σ'_3= 100 kPa displayed a gradual strain hardening behavior, the behavior at R= 90% and σ'_3= 200 kPa is expected to behave similarly. Accordingly, the peak strength angle at R= 90% can be estimated to be approximately equal to the ultimate strength angle reached by a sample compacted at R value slightly greater than 90%. The axial strain level required to mobilize such an angle at σ'_3= 200 kPa is expected to be greater than the axial strain required to mobilize the peak angle at σ'_3= 100 kPa. It is also notable that the maximum mobilized angles were slightly different than those obtained at F_1= 50%.

5.3.3 Behavior of Implicit Mixtures

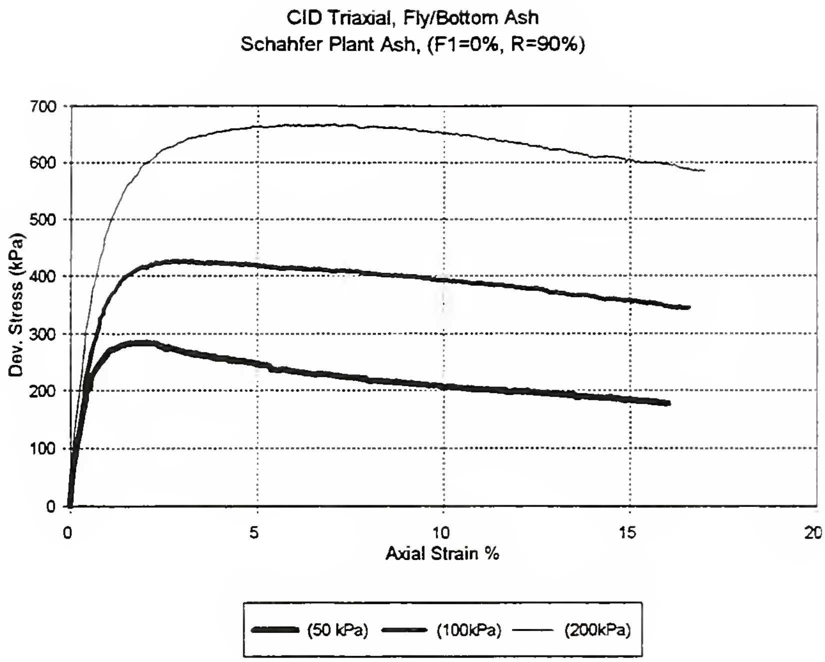
5.3.3.1 Test Results

Figures 5.15 (a) displays the deviatoric stress versus the axial strain of the implicit mixtures containing F_2=22% (sampled from location 1, the discharge location) compacted at R= 95% and tested at the effective confining pressure σ'_3 levels (a=50 kPa, b=100 kPa, c=200kPa). Figure 5.15 (b) displays the volumetric stress versus the axial strain at the tree levels of σ'_3. Subsequently, Figure 5.15 (c) displays the stress path (q-p') diagrams and Figure 5.15 (d) displays the mobilized angle of shearing resistance versus the axial strain. Similarly, the test results of the mixtures compacted at 95% and containing F_2= 53% and 74% are displayed on Figures 5.16 and 5.17 respectively. Figures 5.18, 5.19, and 5.20 display the results for the samples compacted at R=90% and F_2= 22, 53, and 74% respectively.

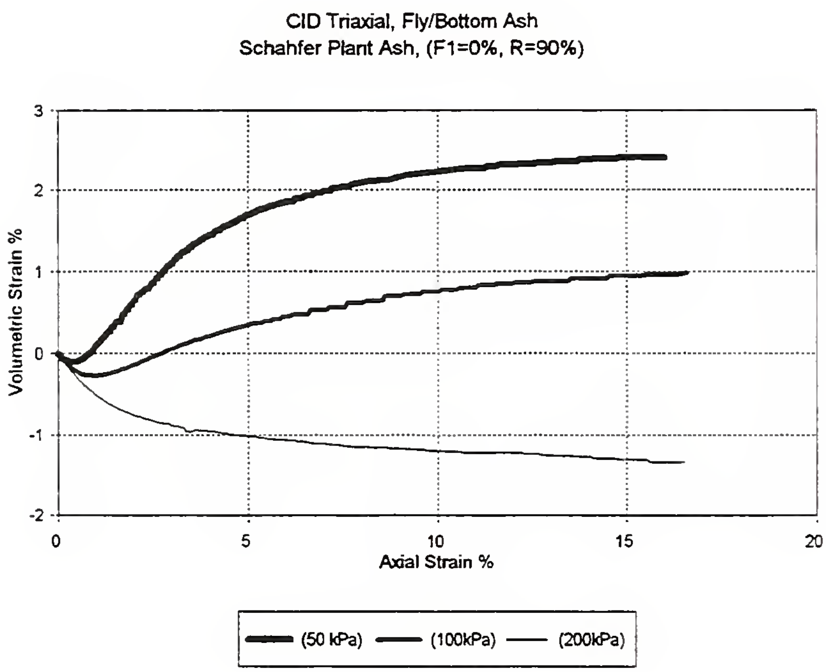
5.3.3.2 Discussion

a- Implicit mixtures compacted at R= 95%

The deviatoric stress versus axial stain curve of the implicit mixtures TXB1H a, b, and c (F_2= 22%) displayed a typical dense granular material behavior similar to the

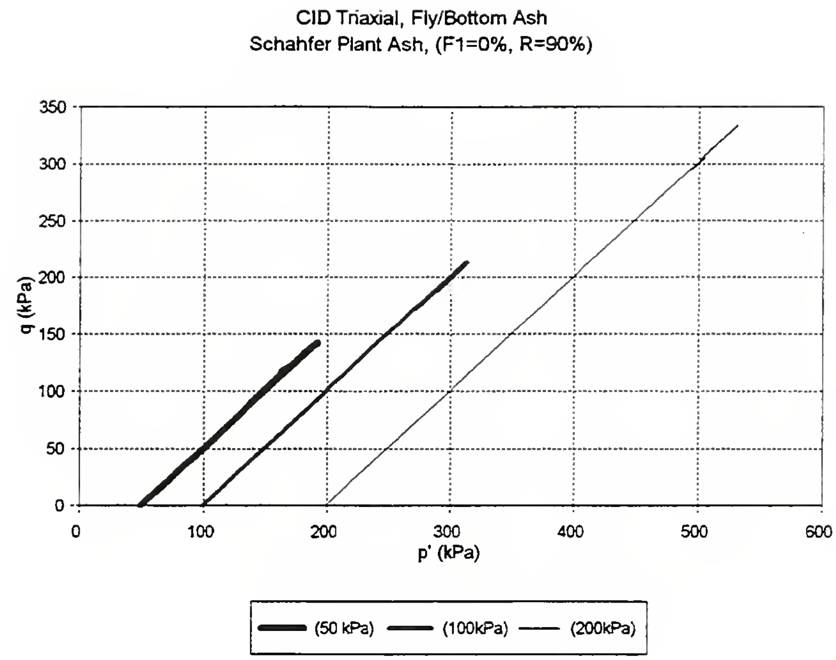


(a)



(b)

Figure 5.10 CID Triaxial Tests on Bottom Ash (F_1 = 0.0%)Compacted at R= 90% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs.Axial Strain. [Continued]



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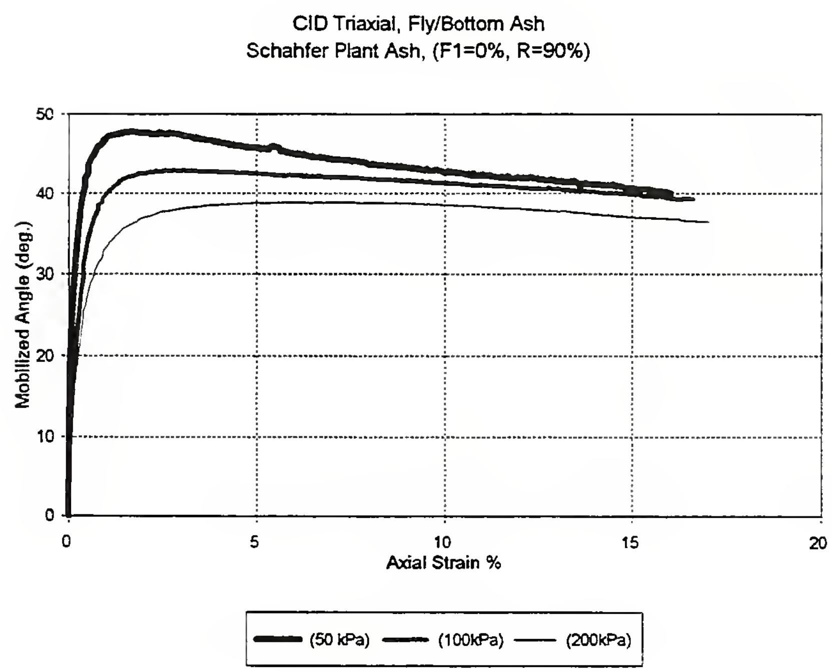
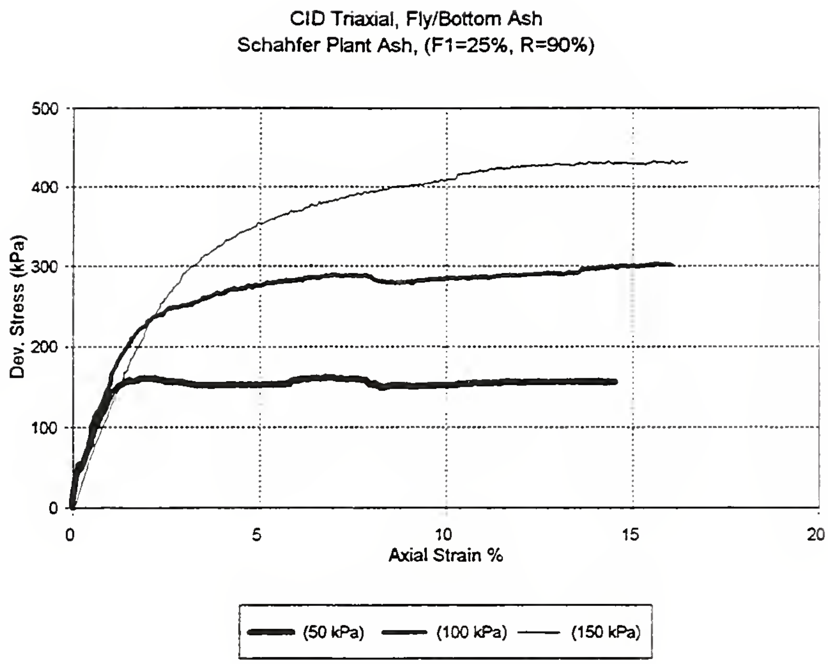
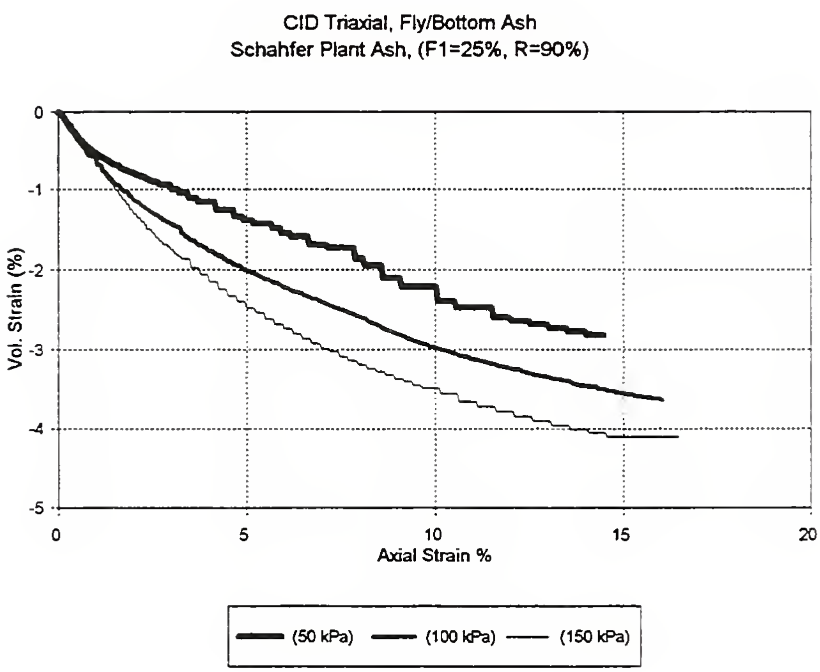


(d)

Figure 5.10 [Continued]

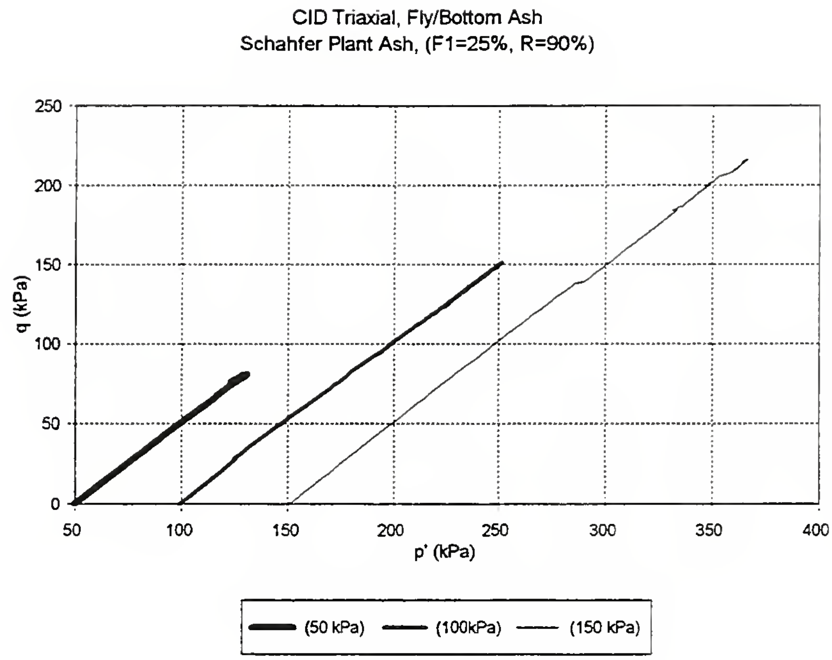


(a)



(b)

Figure 5.11 CID Triaxial Tests on Explicit Mixtures (F_1 = 25%)Compacted at R= 90% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs. Axial Strain. [Continued]



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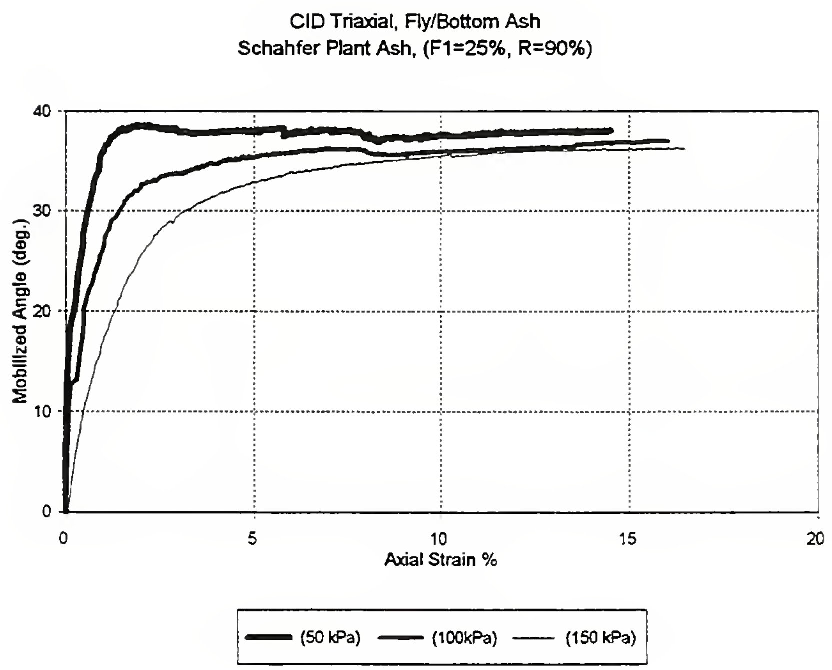
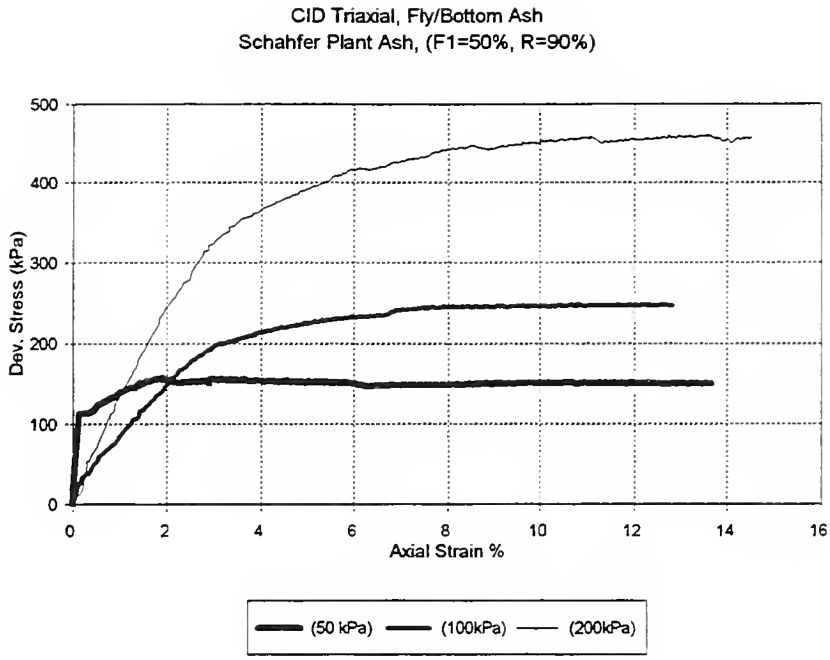
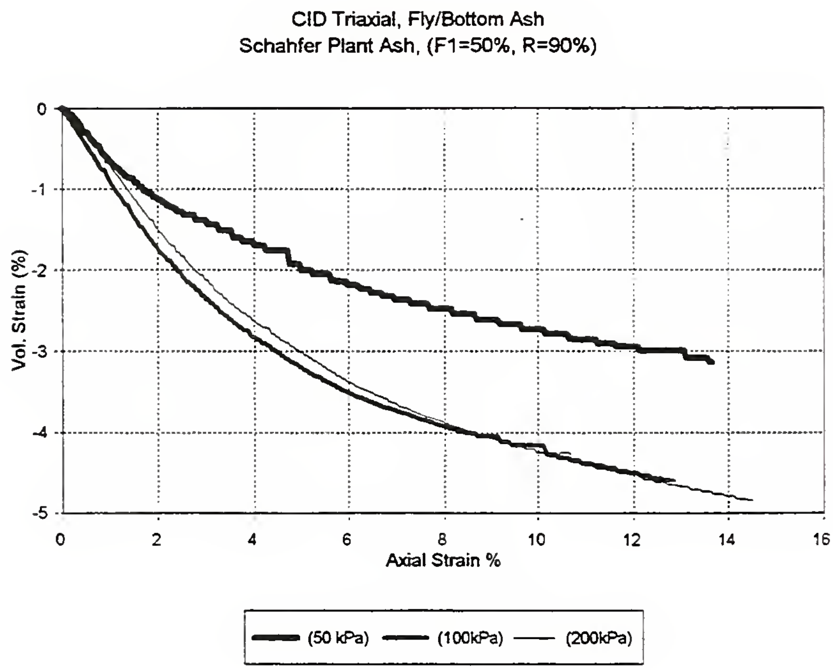


(d)

Figure 5.11[Continued]

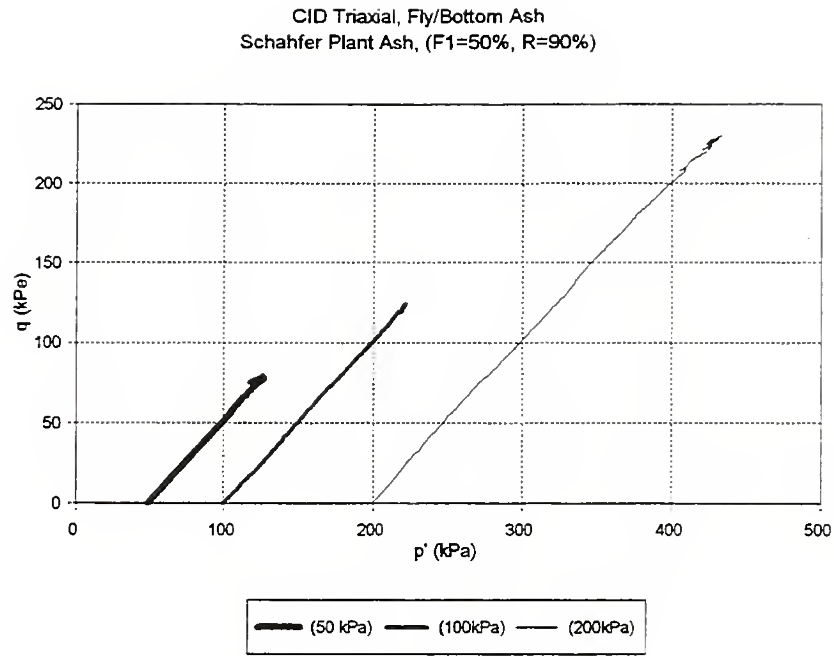


(a)



(b)

Figure 5.12 CID Triaxial Tests on Explicit Mixtures (F_1= 50%)Compacted at R= 90% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs. Axial Strain. [Continued]



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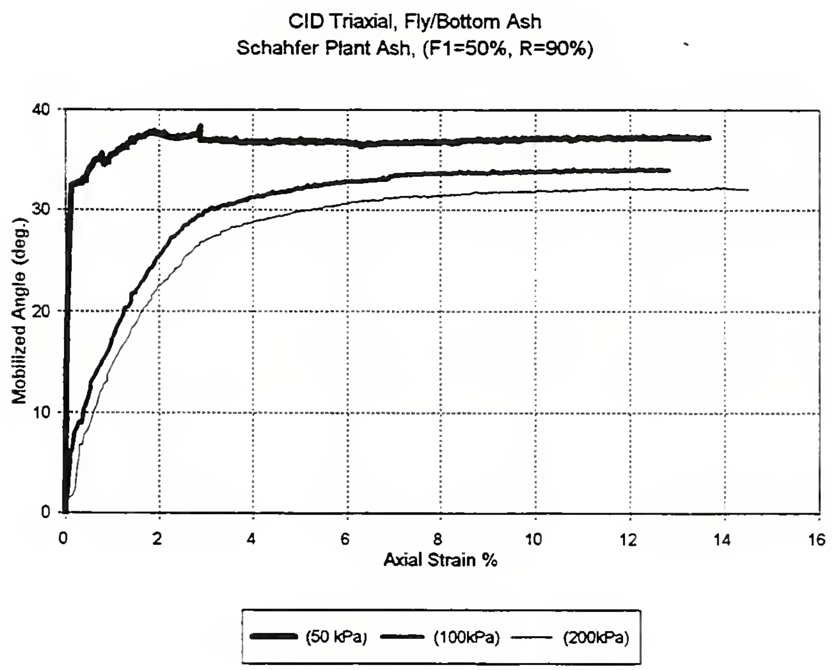
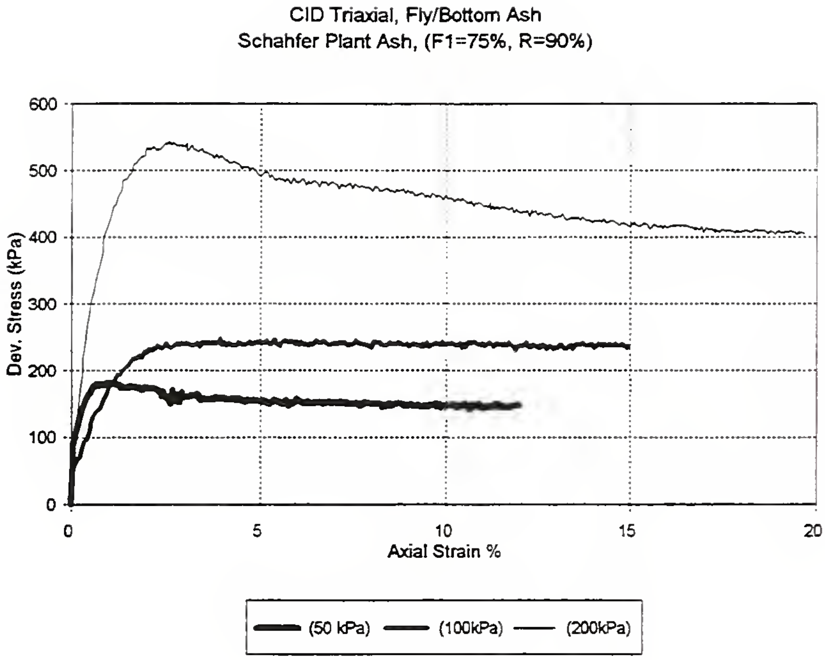
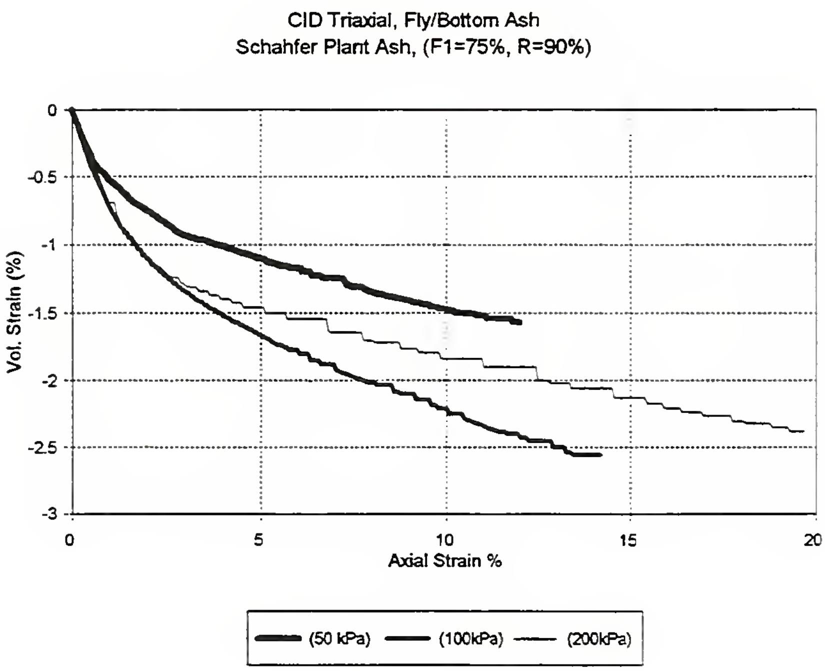


(d)

Figure 5.12 [Continued]

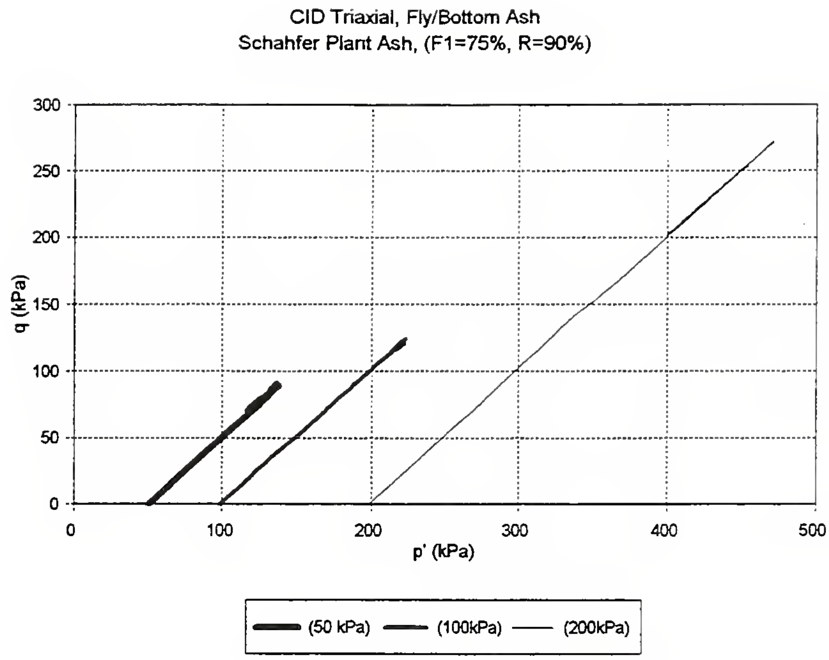


(a)



(b)

Figure 5.13 CID Triaxial Tests on Explicit Mixtures (F_1= 75%)Compacted at R= 90% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs. Axial Strain. [Continued]



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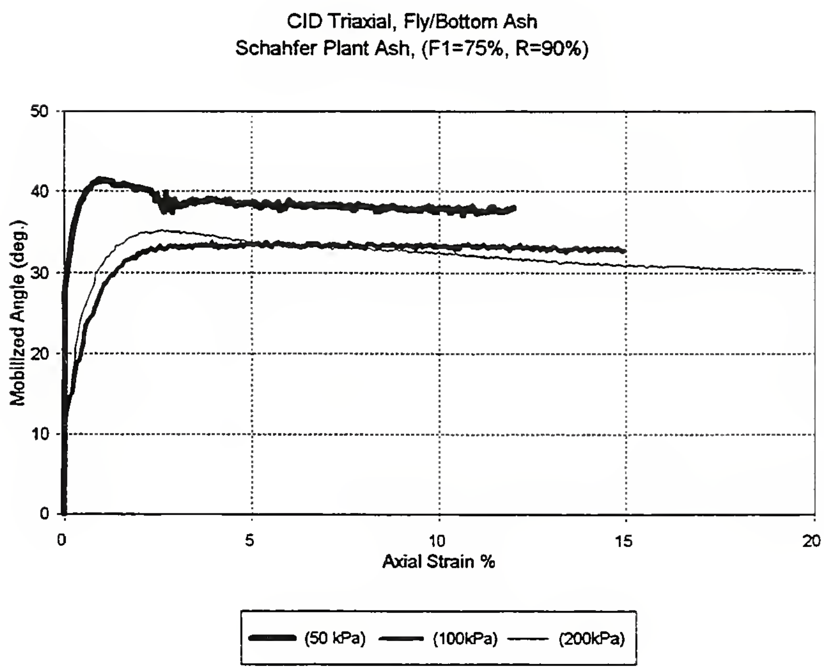

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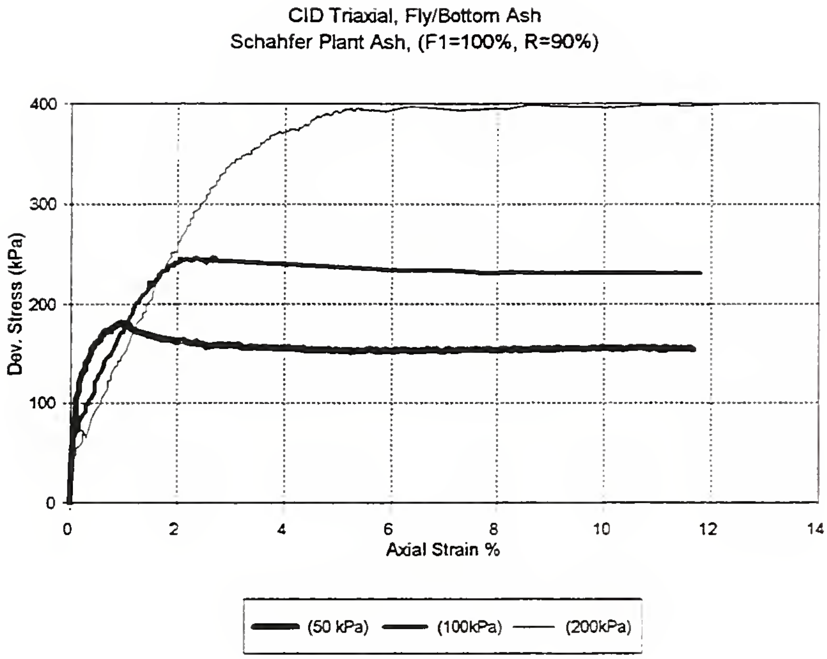
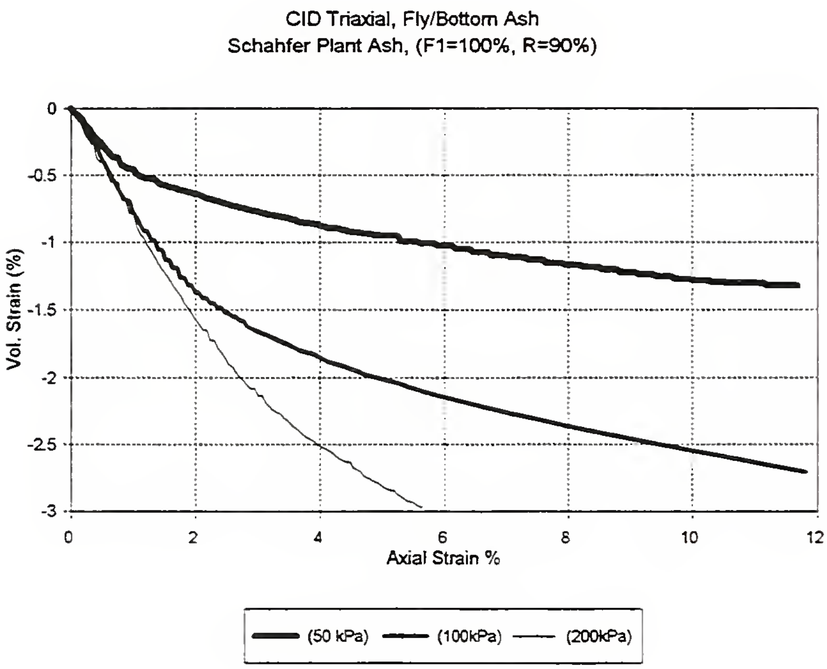
Figure 5.13 [Continued]

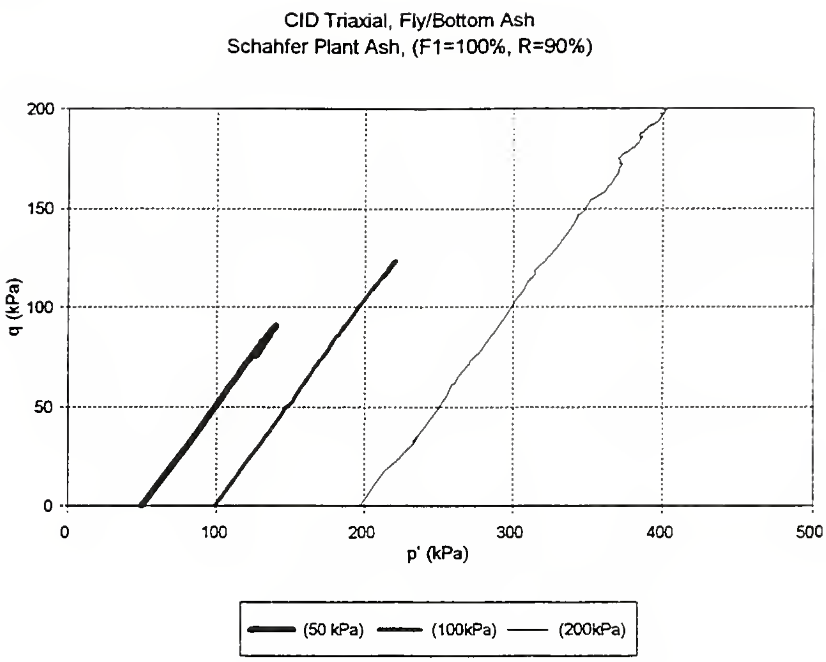


(a)



(b)

Figure 5.14 CID Triaxial Tests on Explicit Mixtures (F_1 = 100%)Compacted at R= 90% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs. Axial Strain. [Continued]



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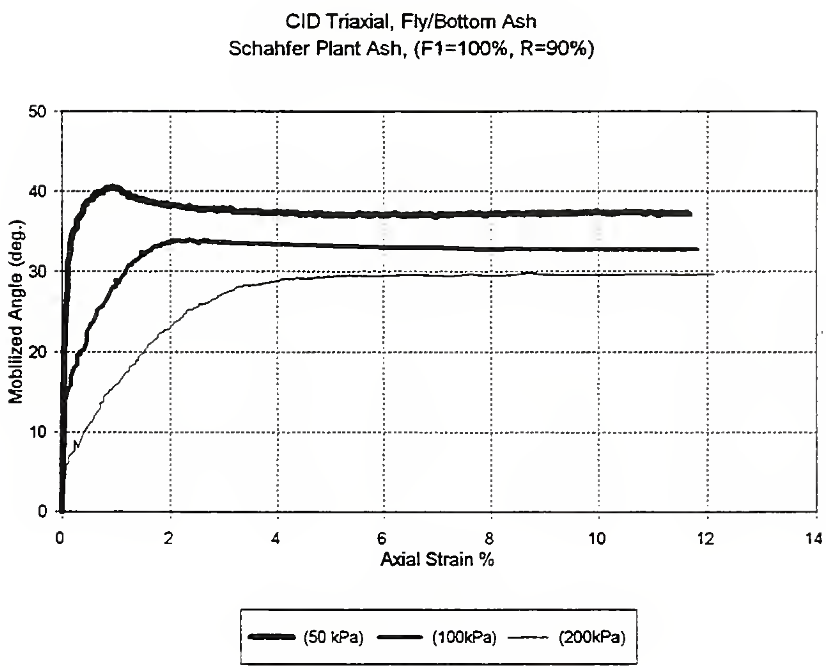


(d)

Figure 5.14 [Continued]

behavior of the bottom ash discussed earlier in section 5.3.1.2. At all three levels of σ'_3, the deviatoric stresses increased to a peak value then decreased as the axial strains increased from zero [Figure 5.15 (a)]. The volumetric strains displayed a dilative behavior [Figure 5.15 (b)]. The maximum value of the ratio ($d\epsilon_v/d\epsilon_a$) is associated with the peak deviatoric stresses. The stress path shows an increase of the values of p′ and q to a peak, then a decrease [Figure 5.15 (c)]. The mobilized friction angles display a stiff behavior as the angles reach their peak values at small axial strains [Figure 5.15 (d)]. At an axial strain level, the mobilized angles decrease as the confining stress σ'_3 increases. The peak strengths are mobilized at axial strains ranging between 1.5 to 2.0%.

As the fines content increases to F_2= 53% , the maximum deviatoric stresses are decreased; however, the deviatoric stresses versus the axial strains display a stiff behavior. Peak stresses are reached at less than 1.8% axial strains, followed by a post peak reduction until shearing at a critical state occurs [Figure 5.16 (a)]. The volumetric strains become dilative only at σ'_3 = 50 kPa, while a tendency to dilation remain visible on the other two samples (σ'_3 = 100 and 200 kPa) [Figure 5.16 (b)]. The q-p′ diagrams display an increase to a peak followed by a decrease [Figure 5.16 (c)]. The strength angles reach their peak values at an axial strain less than 2% [Figure 5.16 (d)]. The mobilized angles decrease as the confining stress increases.

As the fines contents increase to 74% (TXB4H a,b,c), the maximum deviatoric stress further decreases [Figure 5.17 (a)]. The volumetric behavior become contractive, however, the compressive volumetric strains (ϵ_v) are less than 1.2%. The q-p′ diagram displays a peak, followed by a reduction in both p′ and q [Figure 5.17 (d)]. The mobilized angles of shearing resistance reach their peak values at an axial strain which is slightly less than 2%.

b- Implicit mixtures compacted at R= 90%

For the implicit mixture having F_2= 22% (TXB1L a,b,c), as the compaction level decreases to 90%, the maximum deviatoric stresses decrease significantly [Figure 5.18 (a)]. The deviatoric stresses reach their peak values at axial strains ranging between 1%

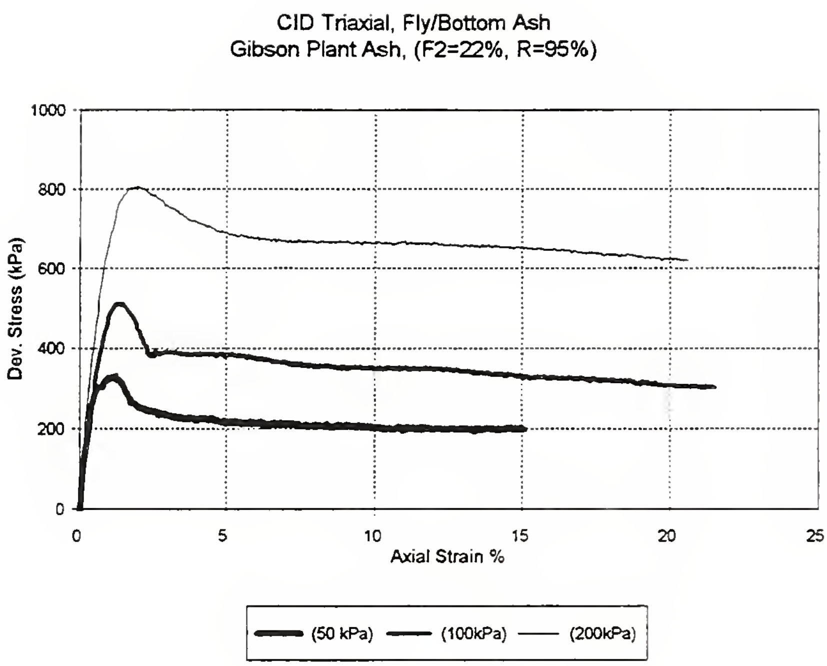
(at σ'_3 = 50 kpa) and 3% (at σ' = 200 kPa). The volumetric strains become more contractive especially as σ'_3 = 200 kPa [Figure 5.18 (b)]. The q-p' diagram displays increasing p' and q to a peak followed by a slight decrease [Figure 5.18 (c)]. The mobilized strength angle reaches a peak value, at axial strains less than 2% for $\sigma'_3 \leq 100$ kPa, then undergoes a slight drop [Figure 5.18(d)]. As the confining pressure increases to σ'_3 = 200 kPa the mobilized angle increases as the axial strains increase until a maximum value is reached at about 2.4% axial strains.

As the fines content increases to F_2= 53% (TXB2L a,b,c), the peak deviatoric stresses decrease [Figure 5.19 (a)]. The volumetric strains become contractive and no tendencies for dilation are observed at any of the three levels of σ'_3 (50, 100, 200 kPa) [Figure 5.19 (a)]. The values of p' and q increase gradually to a peak value. Only at σ'_3= 50 kPa the values of q and p' decrease slightly after reaching the peak. [Figure 5.19 (c)]. The mobilized angles reach maximum at axial strains $\leq$ 6%, except at σ'_3= 50 kPa the stresses increase to a peak and then decrease. The peak deviatoric stresses are mobilized at axial strains ranging from 1.5% (at σ'_3= 50 kPa) to 10% (σ'_3= 200 kPa).

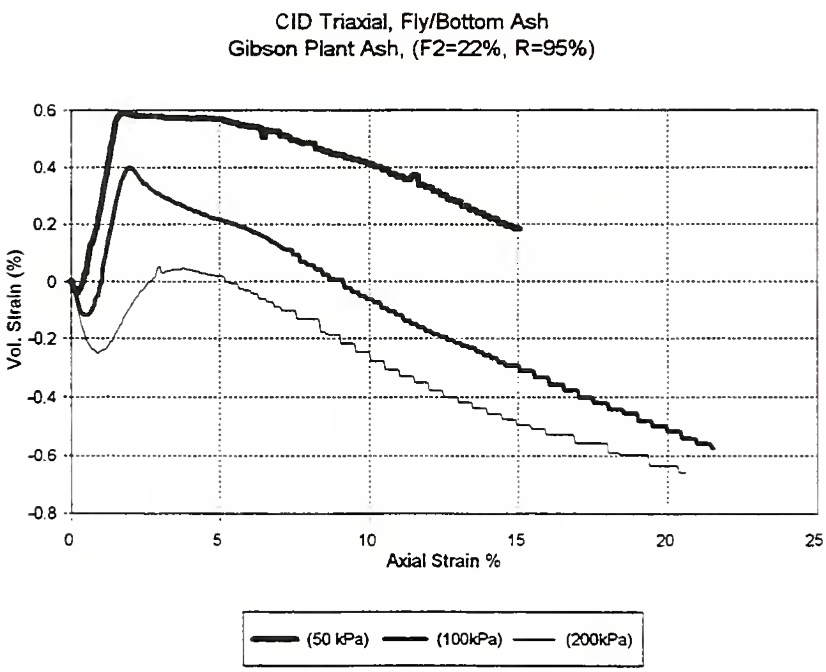
As the fines content increases to 74% (TXB4L a,b,c) , the maximum deviatoric stresses decrease [Figure 5.20 (a)]. The volumetric behavior become more contractive at all three levels of σ'_3 (50, 100, 200 kPa.). [Figure 5.20 (b)]. The values of p' and q increase gradually to a maximum. [Figure 5.20 (c)]. Figure 5.20 (d) display the gradual increase in the values of the mobilized angle of shearing resistance as the axial strains increase. The peak deviatoric stresses are mobilized at axial strains ranging from 4% (at σ'_3= 50 kPa) to 11% (σ'_3= 200 kPa).

5.3.4 Effects of Fly Ash Content on Peak Angle ϕ'_{max}

The peak angle ϕ'_{max} constitutes a measure of the maximum shearing resistance that can be developed by a granular material. For dilative behavior, ϕ'_{max} occurs at the maximum rate of dilation. Normally, the maximum rate of dilation develops at small strains. On the other hand, in an ideal contractive behavior, ϕ'_{max} occurs at larger strains and thus approaches ϕ'_{crit} as the volume decreases. The peak angle ϕ'_{max} depends upon the

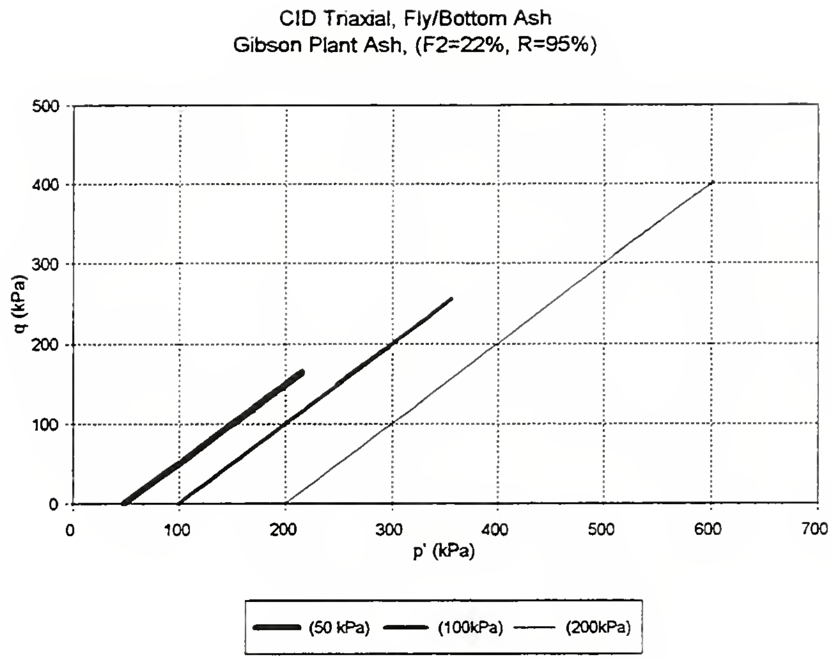


(a)



(b)

Figure 5.15 CID Triaxial Tests on Implicit Mixtures (F_1= 22%)Compacted at R= 95% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs. Axial Strain. [Continued]



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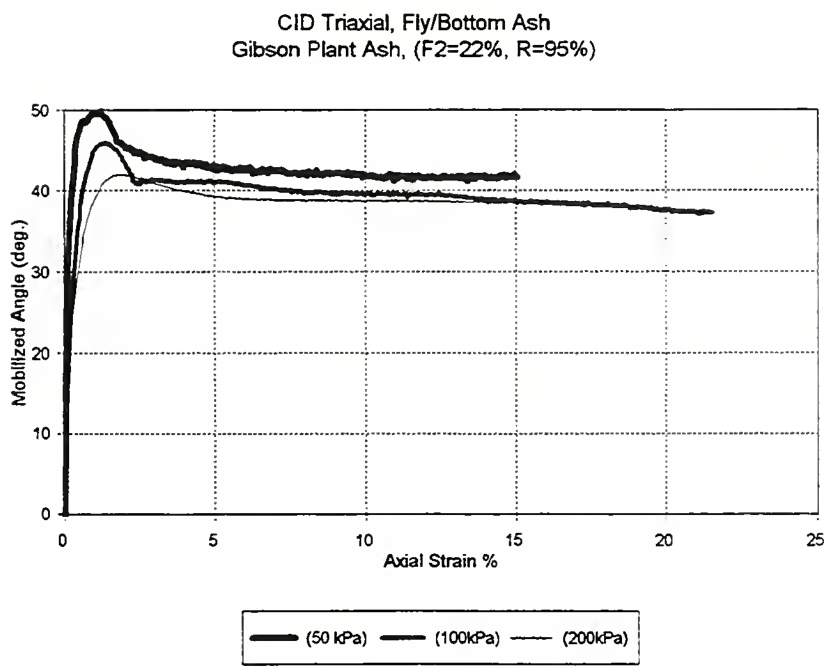
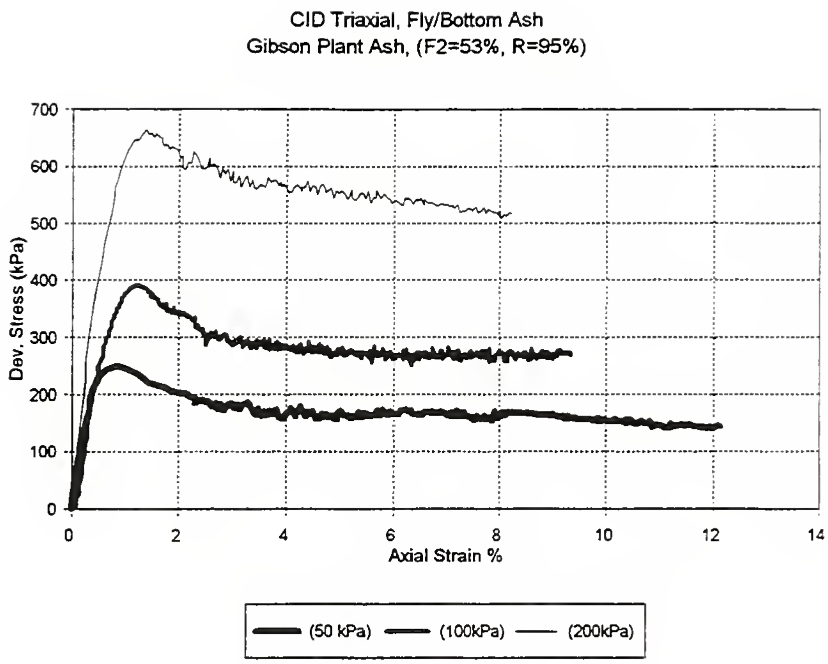
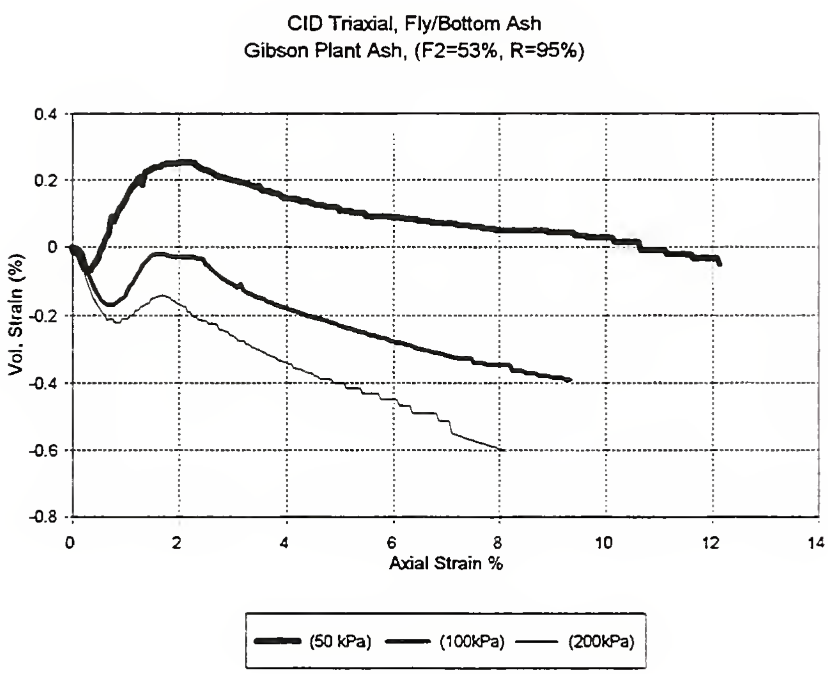


(d)

Figure 5.15 [Continued]

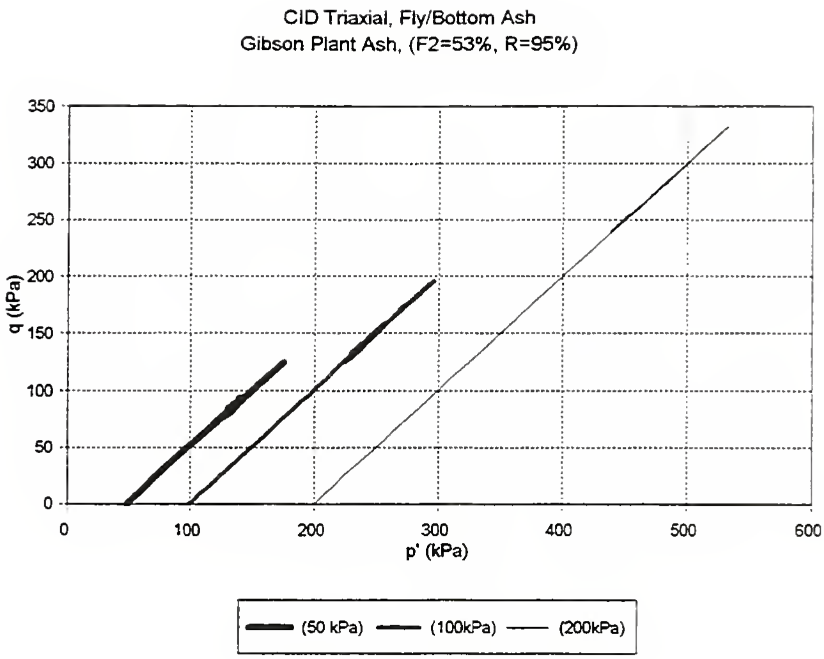


(a)

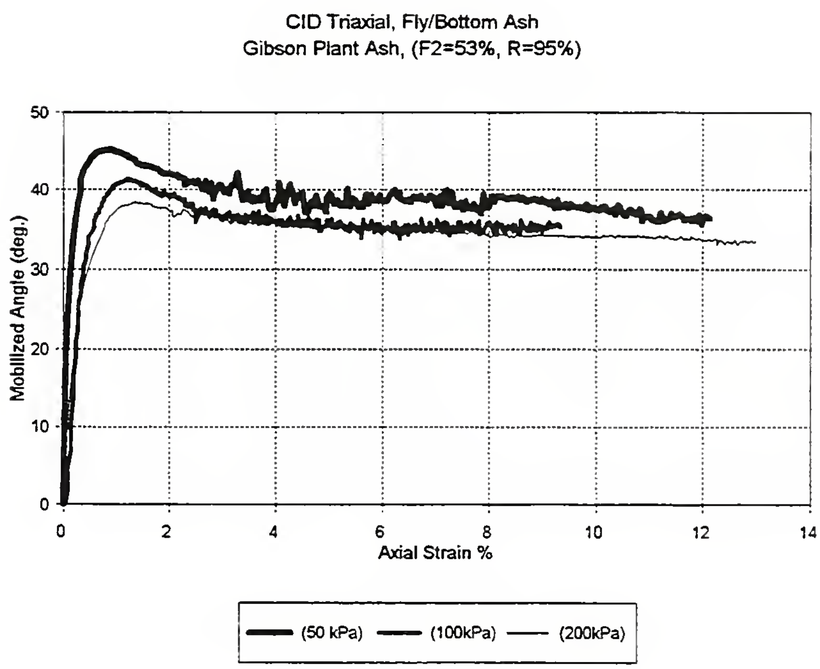


(b)

Figure 5.16 CID Triaxial Tests on Implicit Mixtures (F_1= 53%)Compacted at R= 95% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs.Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs. Axial Strain. [Continued]

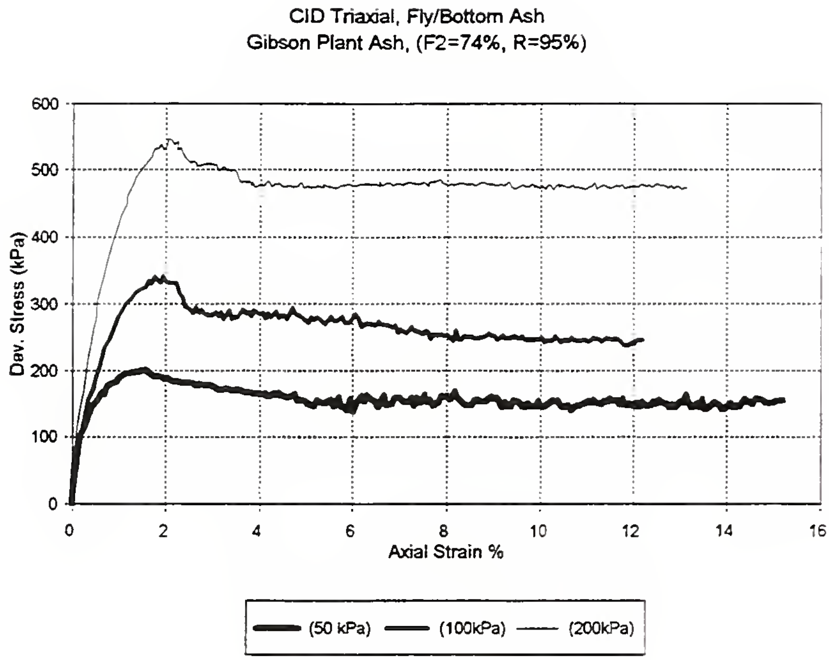


(c)

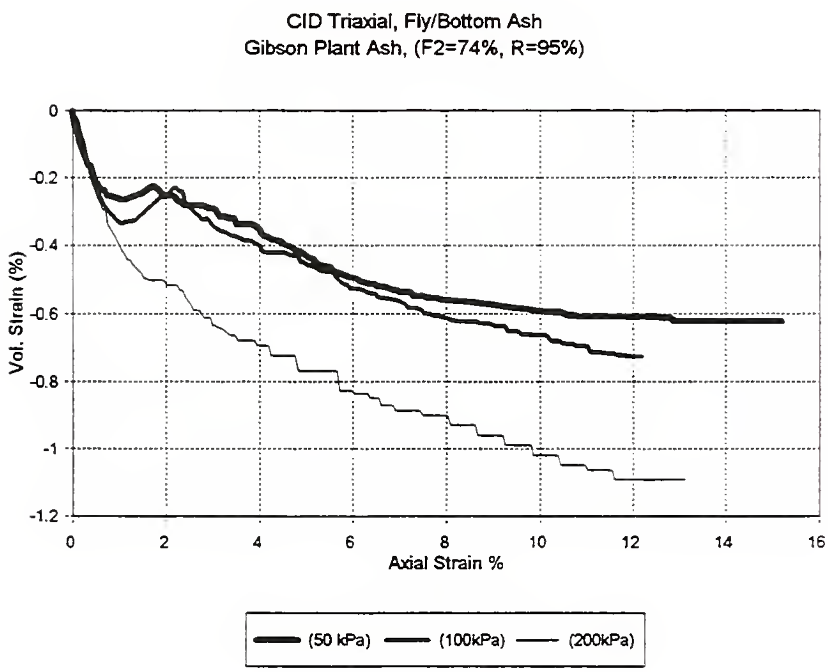


(d)

Figure 5.16 [Continued]

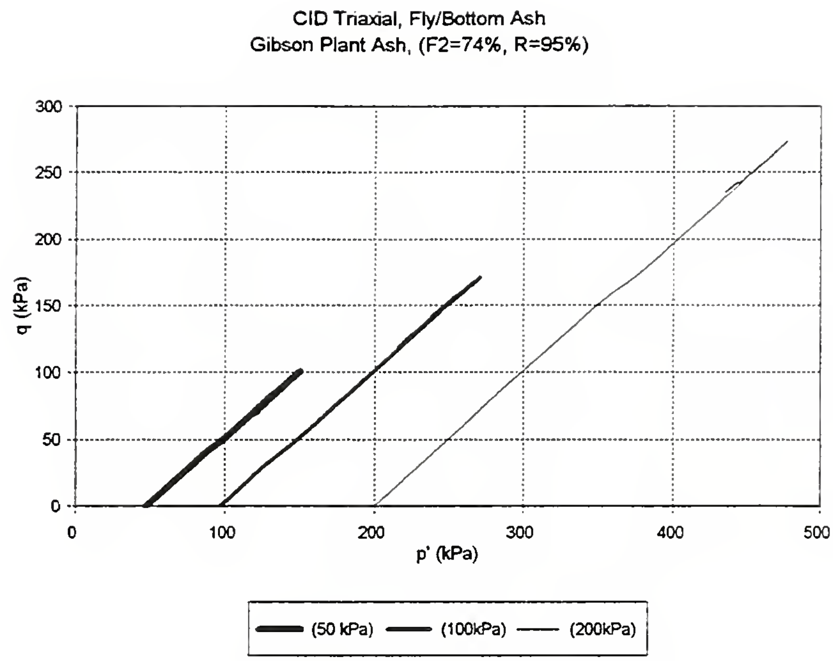


(a)



(b)

Figure 5.17 CID Triaxial Tests on Implicit Mixtures (F_1= 74%)Compacted at R= 95% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs. Axial Strain. [Continued]



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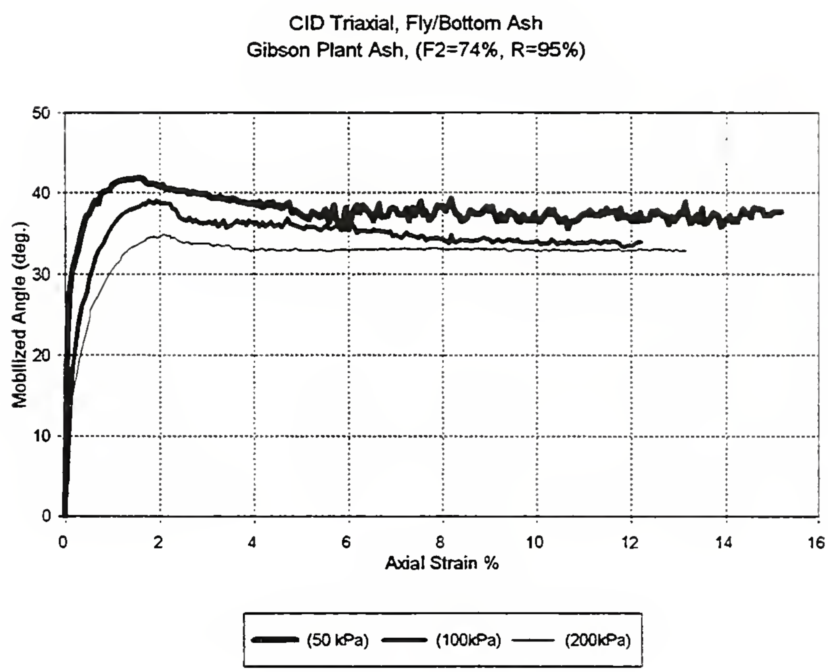

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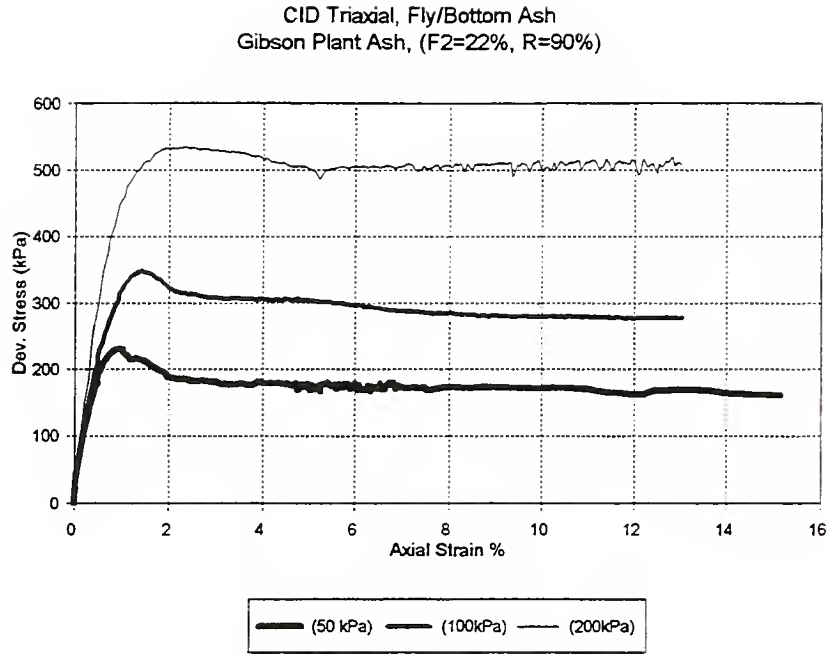
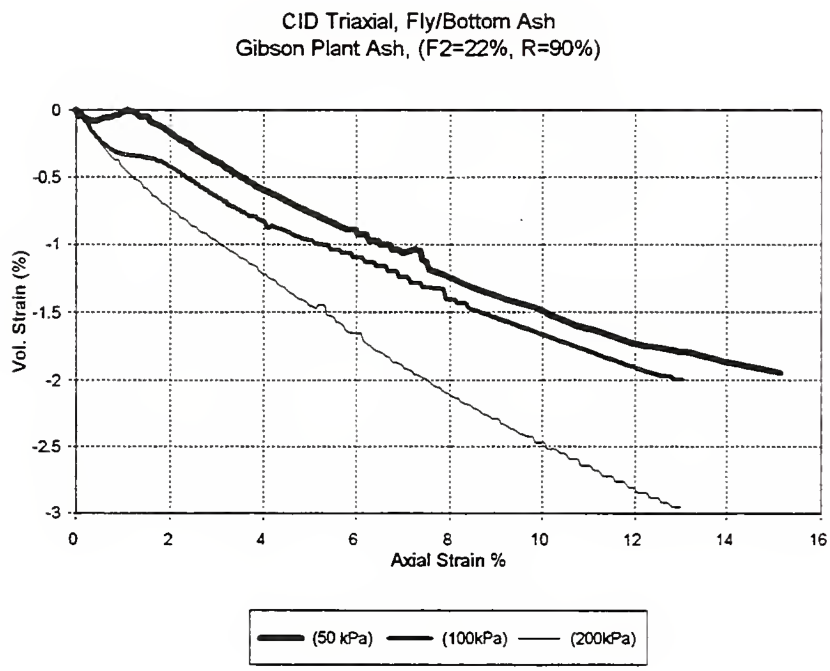
Figure 5.17 [Continued]

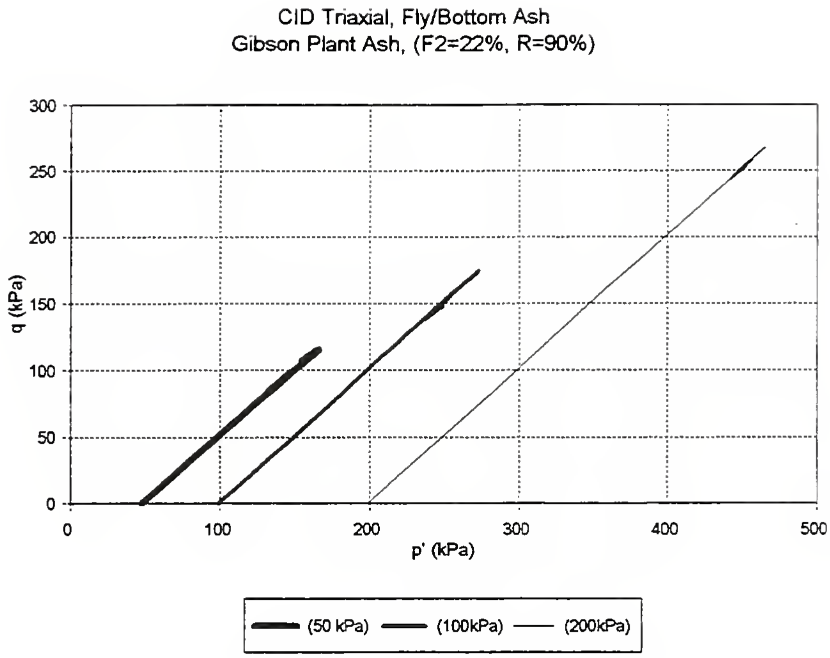


(a)



(b)

Figure 5.18 CID Triaxial Tests on Implicit Mixtures (F_1= 22%)Compacted at R= 90% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs.Axial Strain. [Continued]



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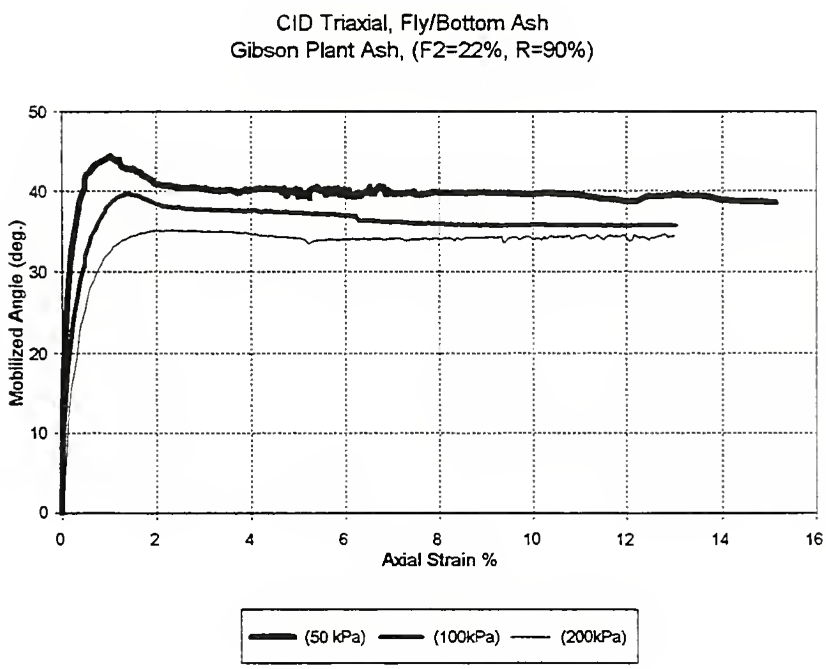
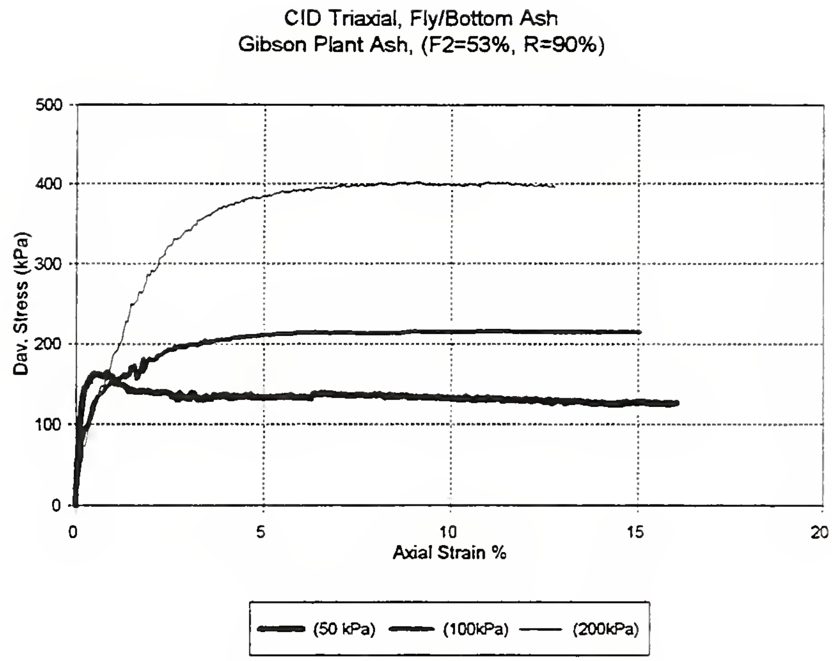
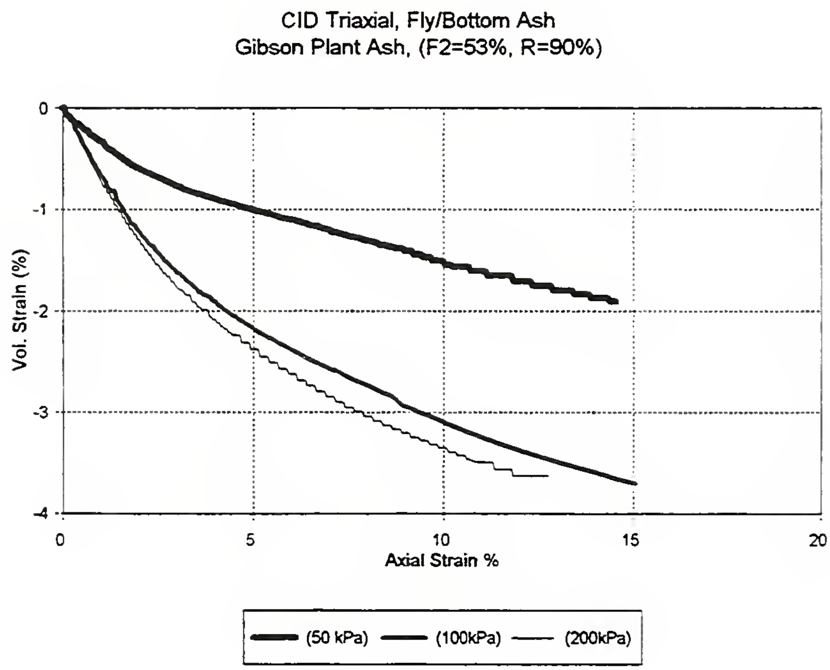


(d)

Figure 5.18 [Continued]

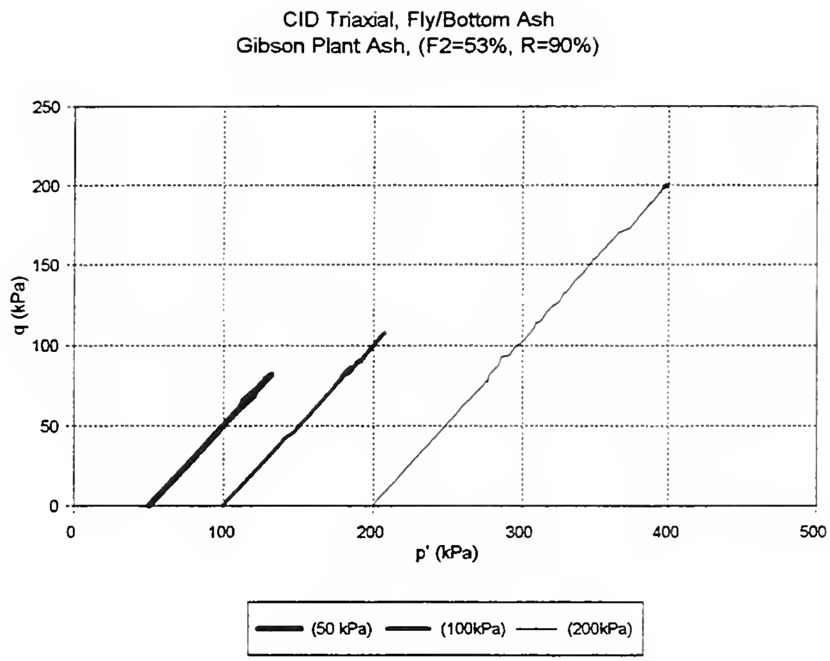


(a)



(b)

Figure 5.19 CID Triaxial Tests on Implicit Mixtures (F_1 = 53%)Compacted at R= 90% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs. Axial Strain. [Continued]



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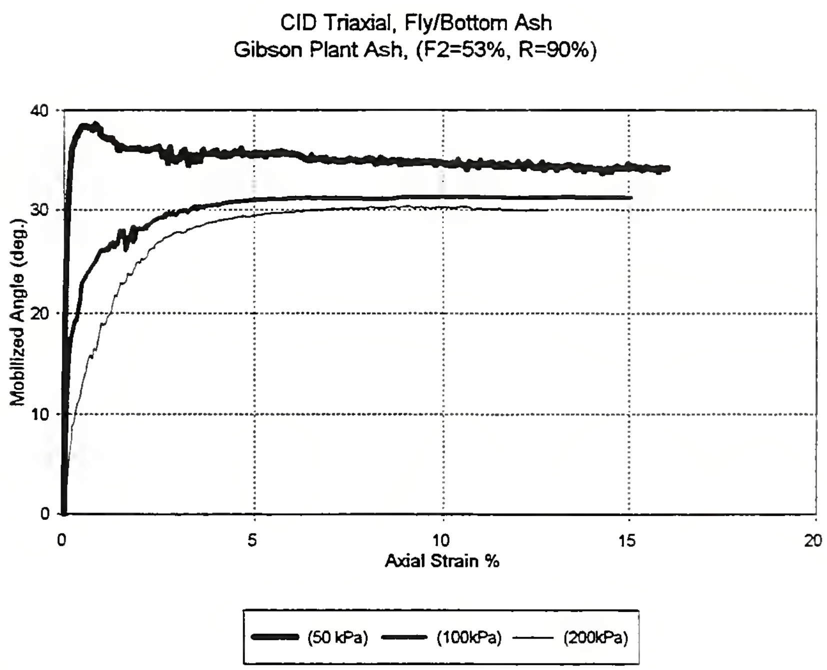

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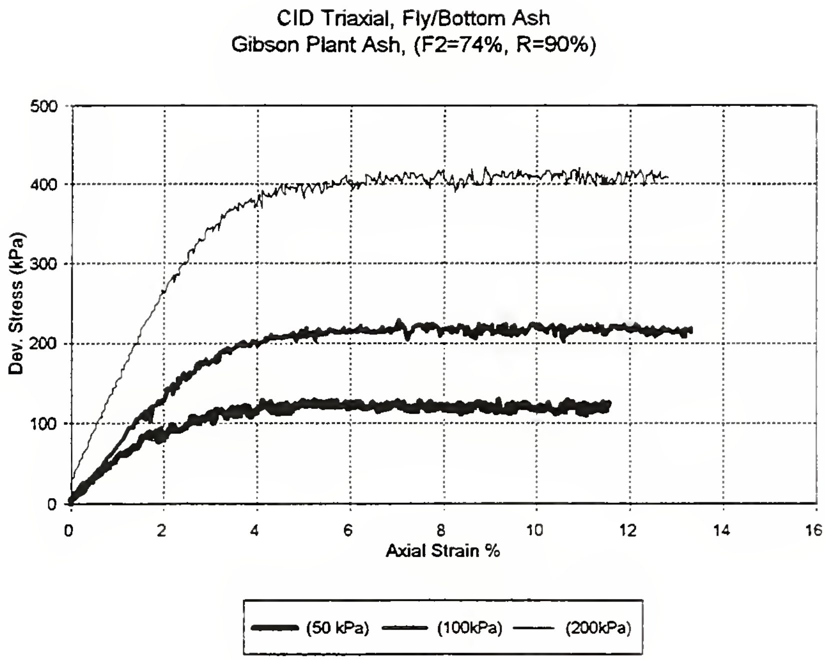
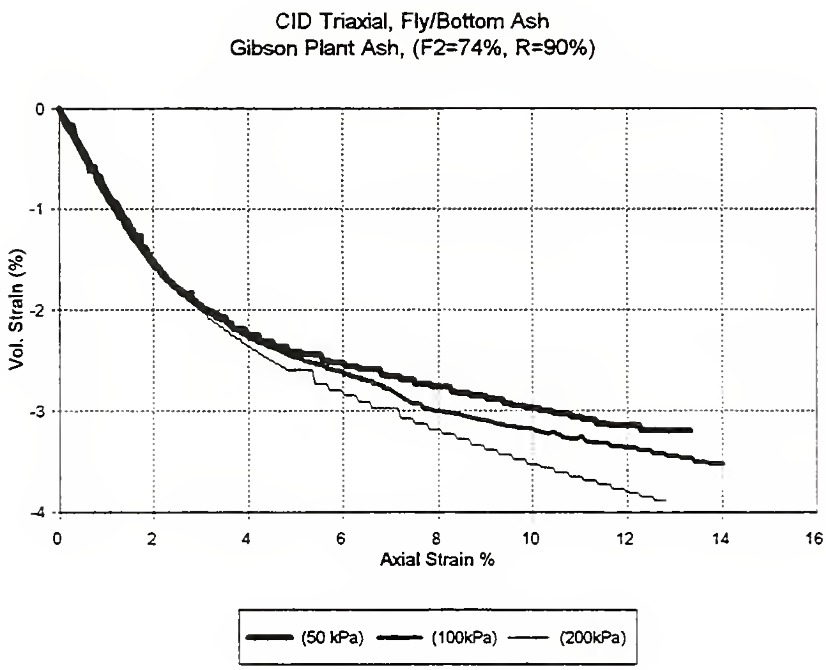
Figure 5.19 [Continued]

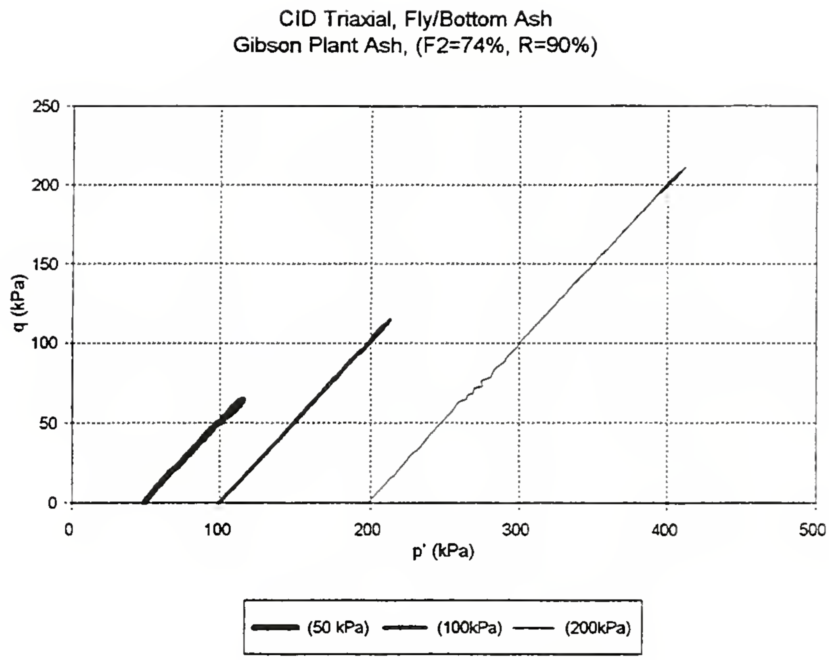


(a)



(b)

Figure 5.20 CID Triaxial Tests on Implicit Mixtures (F_1= 74%)Compacted at R= 90% (a)Deviatoric Stress vs. Axial Strain (b)Volumetric Strain vs. Axial Strain (c)Effective Stress Path (d)Mobilized Angle of Shearing Resistance vs. Axial Strain. [Continued]



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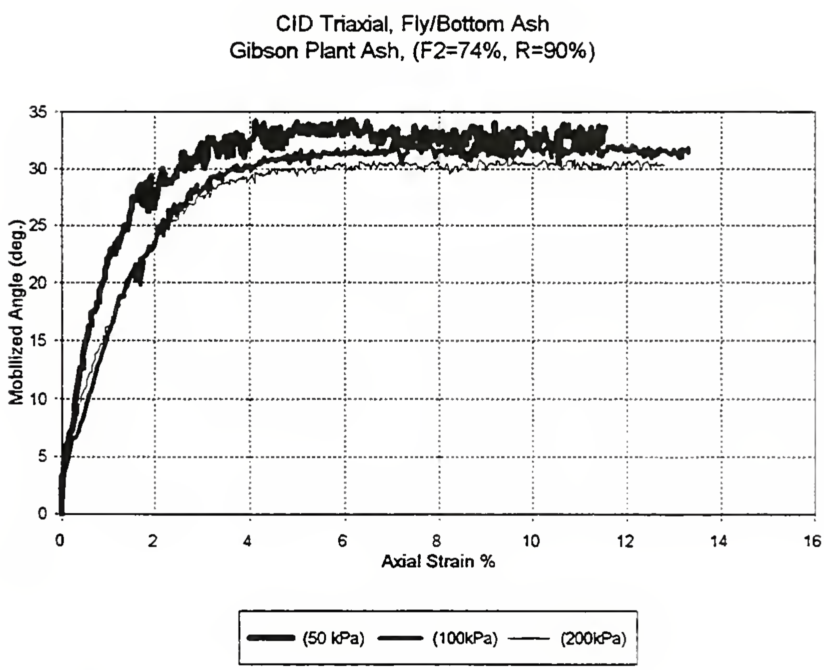

(d)

Figure 5.20 [Continued]

state of compaction (R%), the confining pressure (σ'_3), and the material composition (F_1 or F_2 %).

For the explicit mixtures, at a relative compaction R= 95%, ϕ'_{max} decreases slightly (about 1 to 2 degree) as the fly ash content increases from F_1= 0% to 25 % for the tests at σ'_3 =50 and 100 kPa; while for σ'_3 =200 kPa, ϕ'_{max} increases slightly (about 1.5 deg.) [Figure 5.21(a)]. As the fly ash increases to F_1= 50%, ϕ'_{max} decreases significantly. As the fly ash increases further, ϕ'_{max} changes only slightly. At relative compaction (R) = 90%, ϕ'_{max} decreases rapidly between F_1 = 0 and 50%, but changes slightly as the fly ash increases further ($F_1 \geq$ 50%). This behavior is more strongly observed at the higher confinement levels (σ_3' = 100 to 200 kPa)[Figure 5.21(b)].

For the implicit mixtures at a relative compaction (R) = 95%, as the fines content (F_2) increases from F_2= 22% to 74%, ϕ'_{max} decreases. However, ϕ'_{max} decreases faster between F_2= 22% and 53% than between F_2= 53% and 74%, especially at the higher σ_3' values (100 kPa and 200 kPa) [Fig. 5.22(a)]. For R= 90%, ϕ'_{max} decreases rapidly between F_2= 22% to 53%, but changes only slightly as F_2 increases further ($F_2 \geq$ 53%), especially at the higher levels of confinement (σ_3'= 100 to 200 kPa) [Fig. 5.22(b)].

5.3.5 Effects of Fly ash Content on the Critical Angle ϕ'_{crit}

The critical angle ϕ'_{crit} provides a measure of the ultimate shearing resistance that can be mobilized by the material. In case of an ideal dilative behavior, after reaching peak strength, the strength decreases as the axial strain increases while the rate of dilation decreases. The angle ϕ'_{crit} is reached at large axial strains, as the material is sheared at a constant volume. This is particularly important for the stiff samples, which reach a peak strength and then loose a significant portion of the strength at fairly small axial strains.

For the dense explicit mixtures compacted at R= 95%, at a confining pressure (σ'_3), the critical angle ϕ'_{crit} in the case of F_1 = 25% is similar to that for F_1= 0% [(Fig. 5.23(a)]. Since the peak angle was also substantially unchanged between F_1= 0 and 25%, it may be tentatively concluded that for $F_1 \leq$ 25% and R=95%, the mechanical behavior of the mixture in the triaxial test is mostly determined by the bottom ash. The dilative

volumetric strain ϵ_v , however, was greater for $F_1 = 0$ than for $F_1 = 25\%$ as discussed earlier. As the fly ash increases to $F_1 = 50\%$, ϕ'_{crit} decreases rapidly. As F_1 increases to 75%, ϕ'_{crit} continues to decrease, but then remains practically unchanged between F_1 = 75% and 100% [Figure 5.23(a)]. This was also observed in the case of the loose samples. Hence, it can be concluded that at fly ash contents higher than 75%, the shearing behavior of the explicit mixtures is determined by the fly ash. It was also noticed that the changes in critical strength angle between $F_1 = 25\%$ and $F_1 = 50\%$ are more significant than the changes between $F_1 = 50\%$ and $F_1 = 75\%$. For the implicit mixtures at R= 95%, as the fines content increases from $F_2 = 22\%$ to $F_2 = 53\%$, ϕ'_{crit} decreases. Increasing F_2 to 74% leads to decreasing ϕ'_{crit} only slightly [Figure 5.23(b)].

5.3.6 Dilation of Ash Mixtures

The peak angle (ϕ'_{max}) may be considered as the summation of two angles: the critical state angle ϕ'_{crit} plus an angle due to the soil dilation. Following Rowe's dilatancy theory (Rowe 1962; De Josselin de Jong 1976), Bolton (1986) proposed that $0.8\psi_{max}$ can adequately represent this added angle for a plane strain test (ψ_{max} is the peak angle of dilation in a plane-strain test). In the case of triaxial testing, the peak angle of dilation can only be characterized by the maximum value of the ratio $(-d\epsilon_v/d\epsilon_1)$. Additionally, ϕ'_{crit} may be evaluated at large enough strains where shear occurs at a constant volume (Wood 1990). To estimate the peak secant angle of shearing (ϕ'_{max}), Bolton further presented a correlation that calculates ϕ'_{max} as a function of the mean effective stress (σ'_m), the relative density (I_D), and the critical state angle (ϕ'_{crit}):

$$\phi'_{max} - \phi'_{crit} = 3\ [I_D\ (Q + \ln p_a - \ln (100\sigma'_m) - R_B] \qquad 5.1$$

where:

Q and R_B are regression parameters [Bolton (1986) reported values of Q = 10 and R_B = 1 for silica sands] and $\sigma'_m = [(\sigma'_1 + 2\sigma'_3)/3]$ at peak.

p_a = reference pressure that depends on the units of ${}_m\sigma'\ {}_a$(p = 100kPa = 1 kg/cm^2= 1 tsf).

Equation (5.1) was used to predict (ϕ'_{max} - ϕ'_{crit}) for the triaxial tests on mixtures of F_1 = 0 [TXA1H(a, b, and c) and TXA1L(a and b)] and F_1 = 25% [TXA3H(a, b, and c)], where dilation was observed. At this range of mixtures (F_1 = 0 to 25%), the determination of the maximum and minimum density values are more meaningful than for those containing higher fines contents. The values of I_D for these specimens were 0.66 [TXA1H(a, b, and c)] , 0.43 [TXA1L(a,b)], and 0.75 [TXA3H(a,b,c)]. For these ash mixtures, the value of Q = 10 was found to underestimate the peak value of ϕ'_{max}. A value of R_B =1 was combined with Q = 10.86 for F_1= 0.0 or Q= 10.05 for F_1= 25%, provided reasonable estimates of ϕ'_{max} - ϕ'_{crit} (Figure 5.24) for the ash mixtures. This may be an indication that the tendency for dilation in bottom ash is comparable to that of sands. The bottom ash particles are highly angular in shape, and their surfaces are rough. These two features of the bottom ash particles can lead to significant particle interlocking, hence high dilatancy and strength.

5.4 Summary and Conclusions

Triaxial tests were performed on a range of explicit and implicit mixtures of bottom ash and Class F fly ash to study their volumetric behavior and shear strength. The main purpose is to provide guidelines and recommendations on their utilization in embankment construction focusing on the control of their compaction. Five explicit mixtures from Schahfer Power plant and three implicit mixtures from Gibson Power plant were tested to provide a wide range of possible mixtures. Two groups were formed from each mixture. One group was compacted at a relative compaction R= 95% and the other at R=90%. Three levels of effective confining pressure were used per group. The volumetric changes were monitored as the samples were consolidated under isotropic effective pressure. After consolidation was completed, the samples were sheared under deviatoric stresses to relatively large axial strains 12% to 20%. The majority of the samples displayed a shear plane combined with bulging, in the case of dense samples or a general bulging failure in the case of loose samples. Single-plane shear failures were more commonly displayed by the stiff samples with fly ash contents $\geq$ 50%.

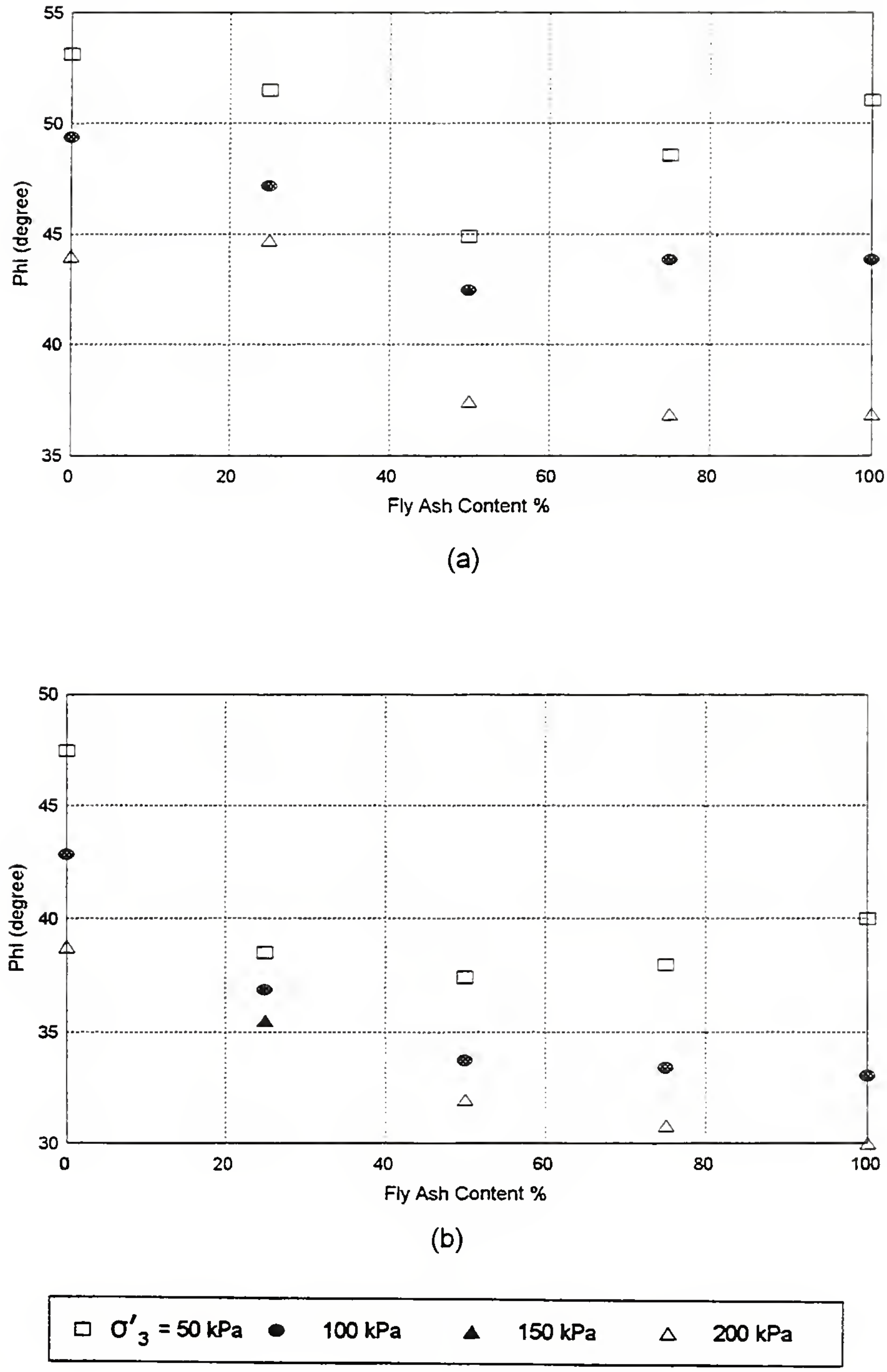

Figure 5.21 Effects of Fly Ash Content (F_1%) and the Confining Pressure on the Peak Angle of Shearing Resistance ϕ'_{max} for Explicit Mixtures (a)R= 95% (b)R= 90%.

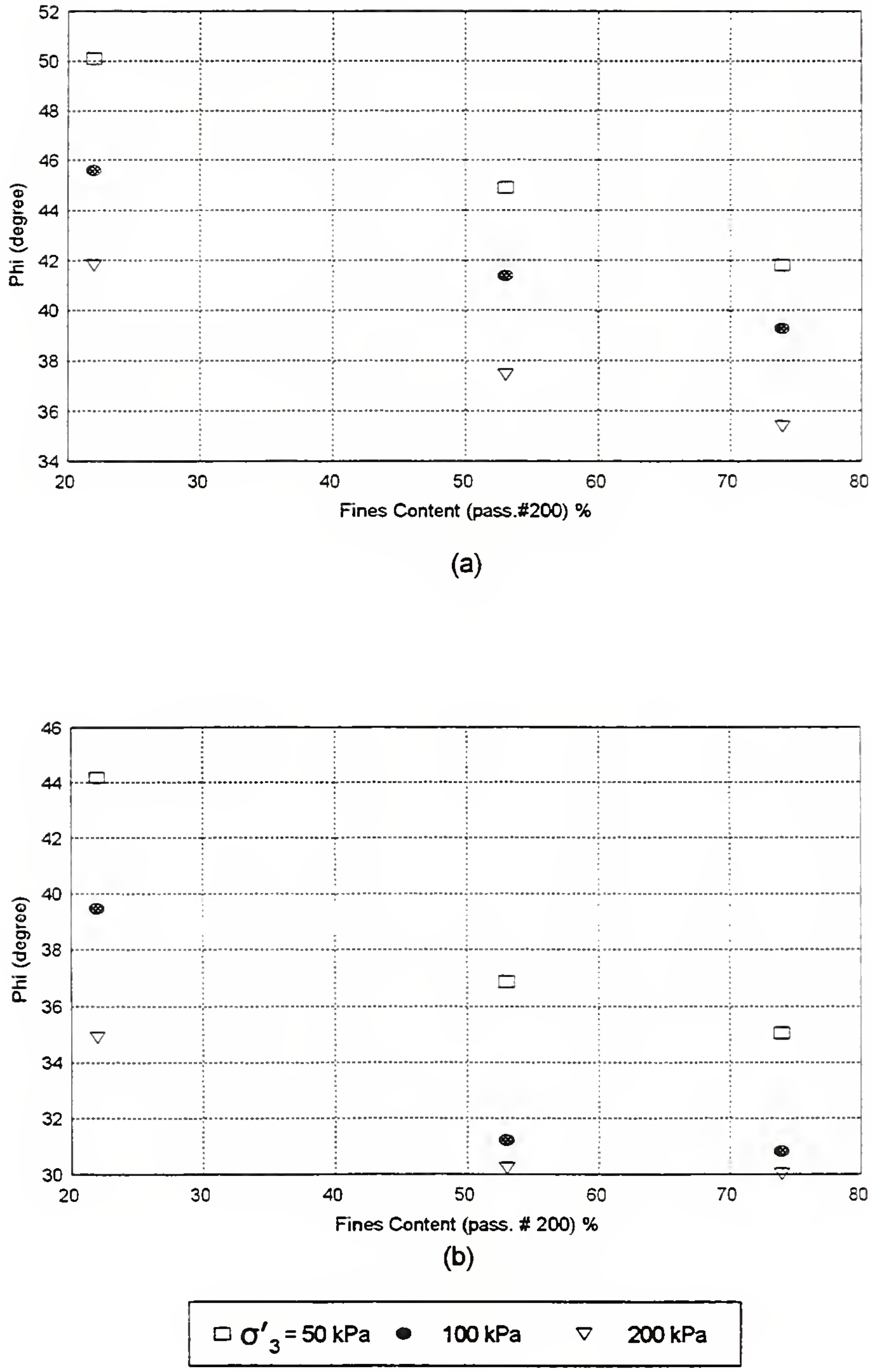

Figure 5.22 Effects of Fines Content (F_2%) and the Confining Pressure on the Peak Angle of Shearing Resistance ϕ'_{max} for Implicit Mixtures (a)R= 95% (b)R= 90%.

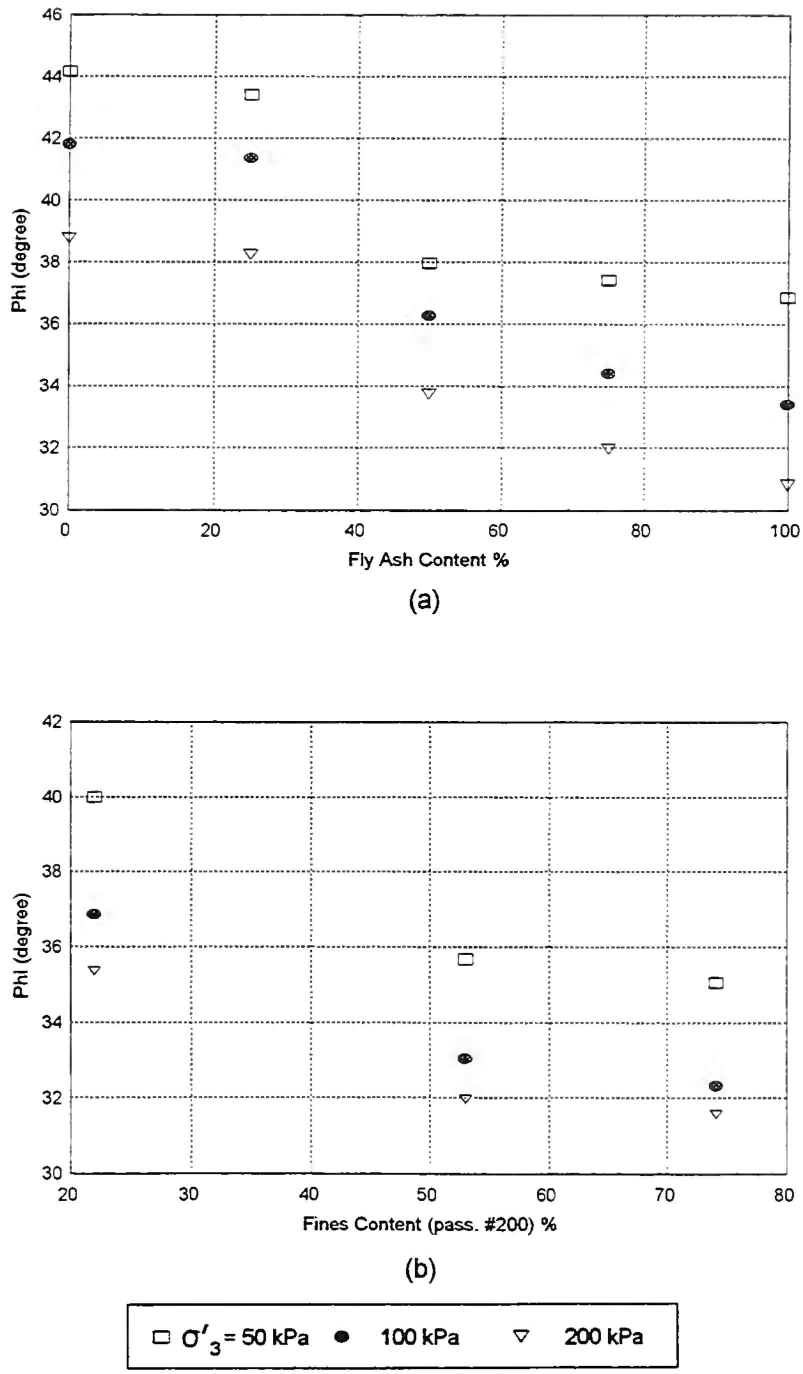

Figure 5.23 Effects of Fly Ash Content ($F_1\%$) (or Fines Content, $F_2\%$) and the Confining Pressure on the Critical Angle of Shearing Resistance ϕ'_{crit} (a)for Explicit Mixtures (b)for Implicit Mixtures.

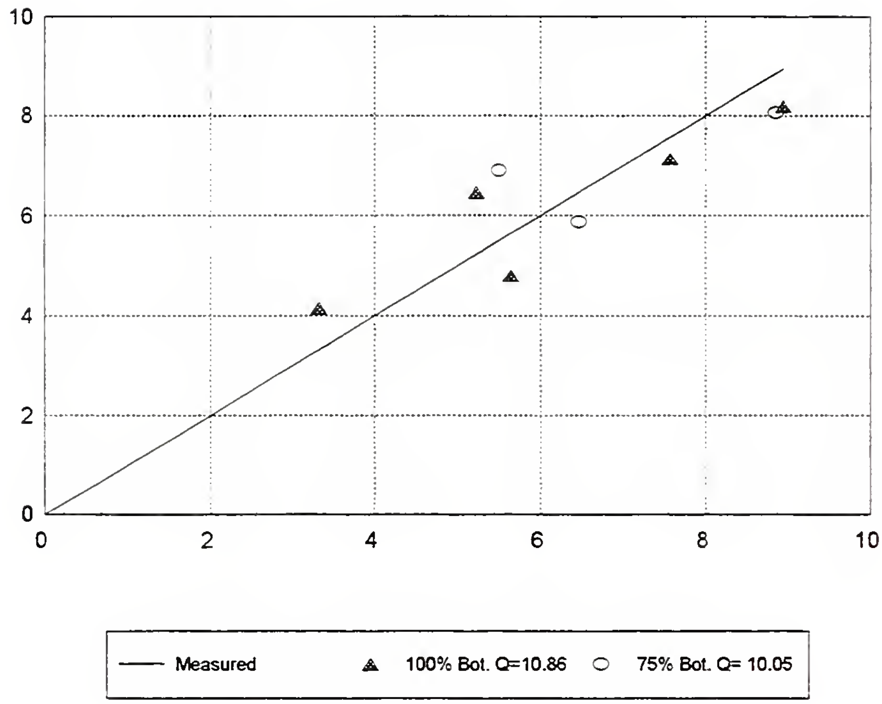

Figure 5.24 Measured vs. Predicted (ϕ'_{max} - ϕ'_{crit}) from Bolton's Correlation.

The following conclusions were made based on the results of the experimental program:

1) At the same confining pressure and fly ash content, the volumetric strain due to isotropic consolidation increases as the relative compaction decreases.

2) At the same fines content and relative compaction, the volumetric strain due to isotropic consolidation increases as the consolidation pressure increases. The pre-stressing effects of compaction can be considered similar to preconsolidation effects. At lower levels of σ'_3, the confining pressure can be below the prestress due to compaction. Hence, the deformations are small and relatively rapid. As the confining (consolidation) pressure increases, the deformations increase. At a certain confining level the prestress is surpassed. The deformations become significantly greater as the confining pressure increases beyond the prestress level. A secondary mechanism that increases the deformations is due to the collapse of weakly bonded (agglomerated) particles.

3) The consolidation rate depends on the hydraulic conductivity of the mixtures. As the fly ash content increases, the hydraulic conductivity decreases and the rate of consolidation becomes slower. However, in the case of dense samples (R= 95%), the samples mainly behave elastically and hence reach the end of consolidation very rapidly. As the relative compaction decreases, the hydraulic conductivity may be greater, but, the prestress pressure can be surpassed and hence large volume changes take place; accordingly, more time is needed to complete the consolidation.

4) The bottom ash displayed an adequate shear strength behavior at the compaction levels tested. The compaction of bottom ash can be easily achieved using vibration, so, it is more beneficial to compact it at $R \geq 95\%$.

5) The shear strength of the bottom ash and Class F fly ash mixtures depend on the confining pressure, the mixture composition (F_1 and F_2 %), and the compaction level (relative compaction R%).

6) As granular materials, the ash mixtures have shear strengths that increase as the effective confining pressure increases. However, at the same strain levels and relative

compaction, the mobilized angles of shearing resistance decrease as the confining pressure increases.

7) The explicit and implicit ash mixtures compacted at 95% displayed adequate behavior in shear and compressibility. The volumetric strain behavior during isotropic consolidation displayed small volumetric strains in the order of 0.5% at σ'_3= 200 kPa. The volumetric strains during shear were either dilative or slightly contractive. The contractive volumetric strains (ϵ_v) were in the order of 0 to 0.6%. The strains increase as the effective confining pressure increases and as the fly ash content increases.

8) At the same fly ash content and effective confining pressure σ'_3, as the relative compaction decreases to R = 90%, the maximum deviatoric stress and the maximum value of q (the shear strength) decrease significantly. Meanwhile, the axial strains required for achieving the maximum shear strength increase. As the fly ash content increases in the mixtures, the axial strains required for maximum shear mobilization increase. The volumetric behavior during shear becomes more compressible. As the content of weakly cemented mixtures increase, the shear strength is decreased further and the volumetric behavior during shear becomes more contractive, especially at the high confining pressures (e.g. TXB4Lc, σ'_3= 200 kPa, R= 90%, F_2= 74%).

CHAPTER 6
APPLICATIONS FOR HIGHWAY EMBANKMENTS

6.1 Overview

This chapter merges the results of the experimental work included in this research with the procedures for utilization of coal ash in highway embankment construction. The state of Indiana ranks fourth in coal consumption for electricity generation. Coal combustion produces waste materials that accumulate at a high rate every year. Bottom ash and Class F fly ash are by far the most generated and most under-utilized coal combustion by-products (CCBP's). Large portions of these materials are environmentally safe when appropriate measures are taken in design and construction. Recycling these materials through large volume utilizations is the most viable alternative to their disposal.

This Chapter focuses, from the geotechnical point of view, on the application of the results of this research to the current practices of building embankments using mixtures of bottom ash and Class F fly ash. The economic, environmental, and construction aspects were reviewed and discussed earlier in Chapter 2. The experimental procedures utilized in this research were described in Chapter 3. The characterization and compaction of ash mixtures were examined and discussed in Chapter 4. The volumetric behavior and the shear strength of the mixtures were investigated and discussed in Chapter 5. Critical discussions of the relevance of this experimental research to building embankments of coal ash mixtures is presented in this Chapter. It includes discussions of the construction and design procedures in light of the topics presented in the earlier chapters.

6.2 Materials Sources and Scope

Bottom ash and Class F fly ash are typically collected from borrow areas in the disposal sites of power plants or from storage silos (in the case of dry fly ash). A borrow area is a location in a disposal site where the ash can be extracted. The type and the quality of ash depends on the coal origin, the type of furnace, the procedure for combustion, the collection techniques and the disposal procedures. These parameters are not typically constant per power plant. Hence it is important to test and investigate the chosen ash (for engineering and environmental properties) at each time a new borrow area is designated. Since in a single borrow area, the ash mixtures may not be homogeneous, the range of mixtures included in a borrow area need to be defined.

This research focuses on the use of environmentally safe coal ash mixtures that are defined by RCRA as nonhazardous and are accepted by the Indiana Department of Environmental Management and the Indiana Department of Transportation. Specifically, these are nonhazardous mixtures of bottom ash and Class F fly ash classified as Types IV and III, as defined by Indiana Administrative Code, 329 IAC 2-9-3 (Table 2.10). Type II of these materials may only be allowed if the pH value is between 5 and 10, and if approved by the concerned departments.

6.3 Embankments of Coal Ash mixtures

Recycling the environmentally-safe coal ash mixtures in construction of highway embankments can be beneficial. However, coal ash mixtures are considered a form of industrial solid waste. The procedures and specifications followed in building the embankments have to deal appropriately with the limitations imposed by the nature of these materials. The coal ash embankments are typically built using techniques of building normal soil embankments, plus techniques used in landfill construction.

The procedures for environmental protection must be compatible with the type of coal ash used (Type IV, III, or II). The coal ash may be totally or partially encased inside a system of a base liner and a cover. The liner and cover system are normally constructed of a low hydraulic conductivity soil (compacted clay), impermeable geosynthetics (geomembranes, e.g Koerner, 1990) or a combination of both types. These

hydraulic barriers can be combined with filters (made of soil or geosynthetics) if needed. Drainage should be provided inside the encasement to avoid embankment saturation and uncontrolled leachate migration.

Mitchell and Jaber (1990) discussed the factors controlling the long-term properties of clay liners, both the desirable (from the engineering point of view) and the required (from the regulatory agencies point of view). They concluded that most clay soils are quite stable materials, since they are near their end point of degradation. The compaction of these liners to a high density makes the hydraulic conductivity of these materials very low. However, two sources may increase the hydraulic conductivity, instability due to chemical interactions from leachates, and cracks due to deformations. It is thus important to choose a medium plasticity clay liner that has a stable composition against the expected leachates. The clay liner must produce low hydraulic conductivity and high enough strength. The clay liners are recommended to be compacted wet of optimum using a high energy. On the other hand, Koerner et. al. (1990) investigated the long-term durability and aging of geomembranes. They discussed the different degradation mechanisms for the geomembranes, concluding that research is still advancing in this area.

Alleman et. al.(1996) investigated the environmental impacts of the coal ash embankment on 56th street, across I-465W, Indianapolis, Indiana. The coal ash was encased inside a system of a sloping base-compacted-clay liner and a clay liner cover (2ft thick) (Figure 6.1). A one foot thick sand layer was placed above the base liner and below the ash to collect any leachates. The environmental analysis included chemical oxygen demand (COD), metal analyses (using inductively coupled plasma, ICP), and Microtox™ bioassay tests. For further details refer to Alleman et al (1996).

Special instrumentation can be installed to monitor the performance of the embankment, both environmentally and mechanically. Monitoring may take place during and after construction. Wells are typically installed to monitor the migrations of leachates from the coal ash to the surrounding soil (Larrimore et al. 1987). Settlement plates as

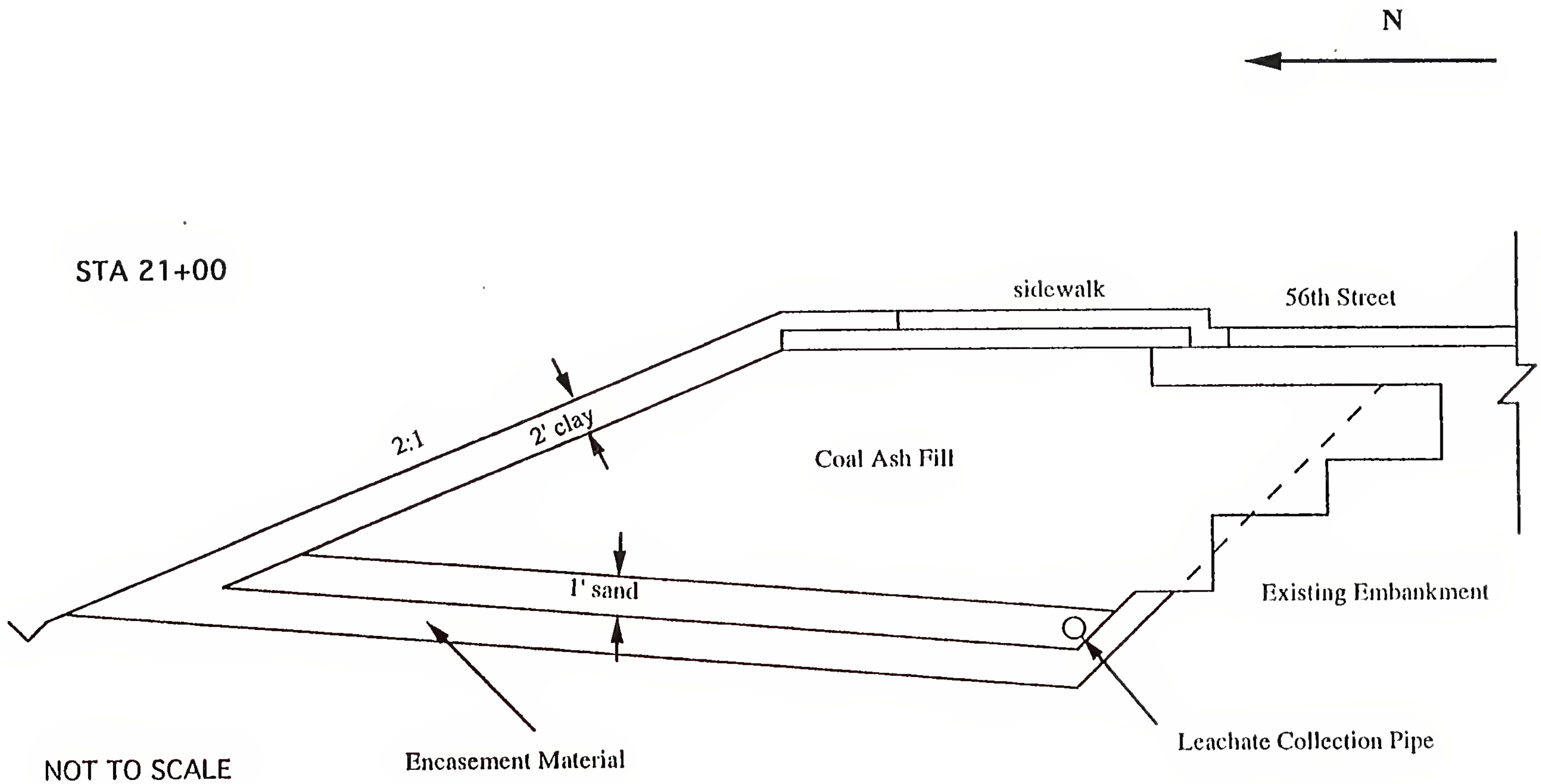

Figure 6.1 Cross Section of 56th Street-West, CCBP Embankments, Indianapolis (Alleman et al. 1996)

well as vertical and horizontal inclinometers may be installed to monitor deformations and movements in the embankment (Salgado 1996).

The following construction sequence may be applied. First, the site is prepared for construction (leveling, cleaning trees and obstructions etc.); then, if needed, a base liner is constructed. Alternatively, the base soil may be compacted if it can provide the required hydraulic barrier, and if the risks from leachates are not significant. Filters may be installed, if required, on top of the base to provide a drainage system for the leachate collection. Loose lifts of coal ash are then placed and compacted one lift at a time. Lifts of the encasement material are also compacted simultaneously with the lifts of the coal ash. The complexity of the base liner (including drainage and single or double liner, etc.) and the cover system are normally dependent on the type of ash (IV, III, or II) and the site conditions.

6.4 Ash Characterization and Processing

The composition of the coal ash mixtures affects the compaction, shear and volumetric behaviors. The microscopic study shows the effects of increasing the fly ash on the fabric of the mixtures. Below the optimum fly ash content, the fly ash particles gradually mask the surface of the bottom ash particles and fill the inter-particle voids. As the fly ash content increases further, the fly ash fine particles gradually separate the bottom ash particles. At a certain fly ash content, the bottom ash particles may no longer be in contact and the behavior of the mixture becomes mainly controlled by the fly ash. Hence, it is important to characterize the ash mixtures appropriately. For explicit mixtures, the fly ash content in the mixture can be described directly. In the case of implicit mixtures, the fines content (the percentage finer than 0.075 mm, sieve #200) is proposed to be used. It provides a more direct technique for the characterization of the mixtures. Moreover, it should be noted that, for implicit mixtures, weak aggregates may be formed from agglomerates of smaller particles. These weak aggregates should be broken such that the fines content and the gradation can be determined accurately.

The sample size and location of sampling also affect samples gradations. Surface samples are normally affected by environmental conditions (e.g. washing of fines due

to rainfall and surface runoff). Small surface samples may not accurately represent the gradation in a location. To provide a better representation of the ash, large deeper samples (80 kg or more) can be obtained and then be reduced using the method of quartering (ASTM D 421, D 422) or the shallow slurry deposition method (Section 3.2.2.2).

Implicit mixtures have to be excavated from a borrow area then transported and stockpiled at the construction site. It is beneficial to plan these procedures such that mixing of the ash is promoted and segregation is minimized. The moisture content may be adjusted in the borrow location or on site. Excessively wet mixtures have to be disked or plowed and aerated. Segregation should not result from the moisture adjustment process. Excessively dry ash needs to be moistened.

Explicit mixtures may be mixed at the appropriate proportions using techniques similar to those used in mixing concrete. Mixing may take place in the plant, during transportation, or at the job site, depending on the feasibility of the mixing process. It may be notable that the additional costs for the mixing must be justifiable. If the mixing process takes place in the power plant, the mixed ash can normally be transported to the site in dump trucks. The ash may be mixed during and after dumping for additional homogeneity. This process and any others that assist in mixing the ash should be implemented.

Stockpiling at the site must follow appropriate procedures such that the siting criteria (Section 2.4.2) are not violated and the ash is stabilized (no dusting or surface erosion occurs). The ash should also be protected from extreme weather conditions. If a top thin layer of the ash becomes frozen, it may be broken and mixed with fresh materials before using it in compaction. Thick deeply frozen ash may not be suitable for use in compaction.

6.5 Compaction of Ash Mixtures

Compaction specification and control are essential for stabilizing the coal ash and achieving the desired stability and performance levels in embankments. For a borrow area, as the range of mixture compositions are defined, a “family” of compaction curves

can be developed as reference curves for this range of mixtures. The compaction curve of a mixture depends on the mixture gradation. The family of compaction curves can be used for determining the degree of compaction (the relative compaction R%) for a mixture with a certain gradation. It can also be used to define an allowable compaction moisture range, and acceptable limits for the mixtures composition.

Limits can be defined on the composition of the mixtures. For example, a range of bottom ash content can be specified (a minimum and a maximum) to facilitate the compaction of the mixtures and achieve a minimum strength requirement. A compatible moisture range must also be specified, such that, the mixtures included in this composition range (bottom ash content to fly ash content range) can be compacted adequately. If the moisture range is not suitable, or the range of mixtures is too wide, excessively dry or excessively wet conditions may result. This point was also discussed in Section (4.4.3). A minimum content, alone, of bottom ash can be specified, only, in the case where a maximum bottom ash content is known and can still be compacted adequately at the specified range of moisture.

For the coarse mixtures containing fines content, F_2 (or fly ash content, F), below the optimum fines content (or the optimum fly ash content), as the fines content changes, the optimum moisture content w_{opt} and the maximum dry unit weight γ_{dmax} change rapidly. This indicates that if the range of mixtures included contain fines less than the optimum fines content, then a narrow range of compaction moisture may be used. If all the mixtures included have fines content greater than the optimum, the change in w_{opt} and γ_{dmax} becomes more gradual as the fines content changes.

In compaction work, either end results or a procedure specification may be applied. A combined procedure may also be applied. The compaction procedures can be developed to maximize the strength. For coal ash mixtures, the composition of the ash is not uniform. To decide on accepting or rejecting the work, the degree of compaction of field compacted samples must be determined. The degree of compaction of the field compacted sample of a certain gradation must be compared against a laboratory compaction curve developed for samples of similar gradation. When a procedure specification is applied, the compaction effort (lift thickness, equipment type, number of

passes, vibration, etc..) and the moisture range must be adjusted such that a minimum degree of compaction (for example $R = 95\%$) is achieved.

When writing the specifications for compaction, it is necessary to consider the variability inherent in the testing procedures. Holtz (1972) presented a summary of a study on the accuracy of controlling compaction using ASTM D-698. He concluded from the study that in practice, a variation within a range of $\pm$ 1.5% resulted when a top quality laboratory performed the compaction test using ASTM D-698-70. This range is slightly higher than the current ranges in practice (e.g., ASTM D-698-91). However, it indicates that variability due to testing is a factor. The variability due to field compaction must also be considered. Very limited literature is available about the variability of field compacted coal ash mixtures.

Alternatively, compaction control may be performed using the relative density approach. This approach may only be used with mixtures of low fines content. In this research, relative density was determined for mixtures with fly ash content up to 25%. Townsend (1972) investigated the effects of fines content on relative density of sands. He cited a value of 12% fines as a generally considered bound placed by the U.S. Bureau of Reclamation (USBR) and ASTM. In his investigation, however, he used fines contents up to 23.1%. The relative density approach is particularly useful because correlations can be constructed between the relative density and measured properties of ash. This technique was long used with granular soils (e.g. Bolton 1986, Al-Hussaini 1972). The fines content in most implicit mixtures is greater than the suitable range for the relative density approach. However, bottom ash and explicit mixtures with low fines content can benefit from this approach. Very limited literature is available about the precision and variability involved in the application of the relative density approach to coal ash compaction control. Further research in this area can be beneficial.

For compacting coarse ash mixtures, composed mainly of bottom ash and very low fines content ($\leq$ 5%), moisture should be adjusted such that the compaction is achieved efficiently without using excessive moisture. These ash mixtures are normally free-draining and have low ability to retain moisture. Coal ash embankments are typically enclosed inside encasement of a system of a base liner and a cover to prevent leachate

migration. If excessive water is used, it will infiltrate though the ash and become trapped by the liner, possibly, causing it to swell and soften.

6.6 Shear strength and Volumetric Behavior

In general, it is noted that the values of the angles of shearing resistance for the dense ash mixtures are comparable to those for dense, well-graded sand and for dense sand and gravel (e.g. Lambe and Whitman 1979). However, the shear strength (in terms of the peak angle of shearing resistance ϕ'_{max}) and the volumetric behavior (due to consolidation or shearing) of the ash mixtures are affected by the degree of compaction, the change in mixture composition, and the confining pressure.

The results of the laboratory testing indicate that adequate behavior was observed for laboratory samples that have a degree of compaction (R) of 95% or greater. The volumetric strains due to consolidation were not significant and the time to 100% consolidation was relatively small. Based on settlement plate records, Brendel and Glogowski (1989) reported that the settlements in the fly ash of the East Street Valley Expressway embankment were completed during the construction period (Section 2.4.4.1). Alleman et al. (1996) also reported similar results for a recently completed embankment of coal ash mixtures. This embankment was the first demonstration project for building embankments of coal ash mixtures, in Indiana.

Furthermore, for the samples compacted at R= 95%, the maximum deviatoric stresses were achieved at low levels of axial strains. This indicates that only small strains are required to mobilize the resistance. In other words, the material does not have to experience large strains to mobilize the maximum resistance. For highway embankments, this can be considered an advantage. However, in the case of dense samples of high fly ash content, the strength also drops rapidly towards an ultimate strength as the strains increase beyond the peak strength. The volumetric strains during shear were either dilative (especially at low confining pressures, σ'_3=50 kPa) or slightly contractive (especially at high confining pressure, σ'_3= 200 kPa). It was also observed that the behavior of the dense samples with fly ash contents F_1 (or fines content F_2) equal to or less than 25% were mainly determined by the bottom ash.

On the other hand, the samples compacted at R= 90% displayed a contractive behavior. Only two samples of bottom ash, those tested at σ'_3 =50 kPa and 100 kPa, displayed a slightly dilative behavior. Furthermore, the samples compacted at R=90% displayed greater volumetric strains during consolidation and the time for consolidation was relatively longer than the samples compacted at R=95%. It was also noted that the behavior was mainly determined by the fly ash for the loose samples at fly ash contents F_1 (or fines content F_2) equal to or more than 50%.

6.7 Applications To Slope Stability

The angles of shearing resistance are normally used to analyze the stability of side slopes and the bearing capacity. The stability of slopes may be checked using one of the methods based on limiting equilibrium. Duncan (1992) reported that the choice of the particular method to use is not very critical, as long as the method satisfies the moment and force equilibrium (e.g., Janbu, 1973; Morganstern and Price, 1965; Spencer 1967). The choice of the parameters involved (ϕ', the dry unit weight, and problem geometry) is more significant. This following discussion aims at providing insight into the factors involved.

The limiting equilibrium method is based on the following assumption: as the strength of the material is reduced by a particular factor (F.S.), the whole slope is on the point of failure. Unless the field compacted samples can be proven to display strength behavior similar to the laboratory compacted samples, it may not be warranted to use peak strengths derived from the laboratory tests in the design. Lowe (1969) also reported that it is more logical to consider the strength at large strains rather than the peak strength when using limiting equilibrium to analyze a slope.

The results provided in Chapter 5 are based on testing samples prepared using moist tamping. The samples were prepared under "laboratory controlled" conditions. And even in such case, variability may have occurred within the samples, since the material is not made of uniform aggregates. Duncan (1992) added that unless the peak strength can be mobilized over a wide range of strains, there is no guarantee that it will be mobilized simultaneously along the full length of the slip surface. Furthermore, the

confining pressures will vary along the slip surface leading to reducing the strength angle. In some locations, the stresses may be high enough to drive the material to behave "loosely". Duncan concluded that using the residual stress is the only fully reliable approach. In the field, the degree of compaction may possibly exceed that of the laboratory. Furthermore, the use of vibration in the field may lead to a stiffer soil fabric. However, the variability in the mixtures may lead to differences in the degree of compaction of the mixtures. Reduced degree of compaction will result in softer behaviors.

Advanced software packages, e.g. PCSTABL 5M; (Acheylios, 1988; Siegel et al. 1981; Boutrup and Lovell 1980) or similar, may be used to model the exact ash geometry and properties including the encasement and foundation soil layers. The following simplified analysis, however, is aimed at gaining insight into the factors involved. Assuming failure were to occur in an infinite homogeneous slope of a dry cohesionless ash mixture, the factor of safety can be calculated as,

$$F.S. \; = \; \frac{\tan\phi'}{\tan\beta} \qquad 6.1$$

where, ϕ' is the angle of shearing resistance and; β is the slope angle, and $\tan\beta = 1/h$.

Figure 6.2 displays factors of safety versus ϕ' for h values ranging from 2 to 3. If a factor of safety of 1.5 is to be required and the mixture is a loose fly ash rich mixture (F_1 = 75% to 100%) with $\phi' = 30°$, then an " h" value of 2.6 (i.e. A slope of 2.6:1) at least is required. On the other hand, if the mixture is a denser coarser mixture and $\phi' = 38°$, the slope may be steeper and h = 2 (i,e. a slope of 2:1). If a range of mixtures were to be used, the slope angle should be designed such that the slope remains stable at all conditions. The materials should be reliably compacted to a dense enough state such that the shear strength is sufficient to satisfy the stability requirement (a minimum F.S. is obtained). Otherwise, if the mixtures range is too wide and a targeted strength angle may not be obtained, then the slope angles must be decreased, and an alternative material or a retaining structure may be used. Limitations on the right of way

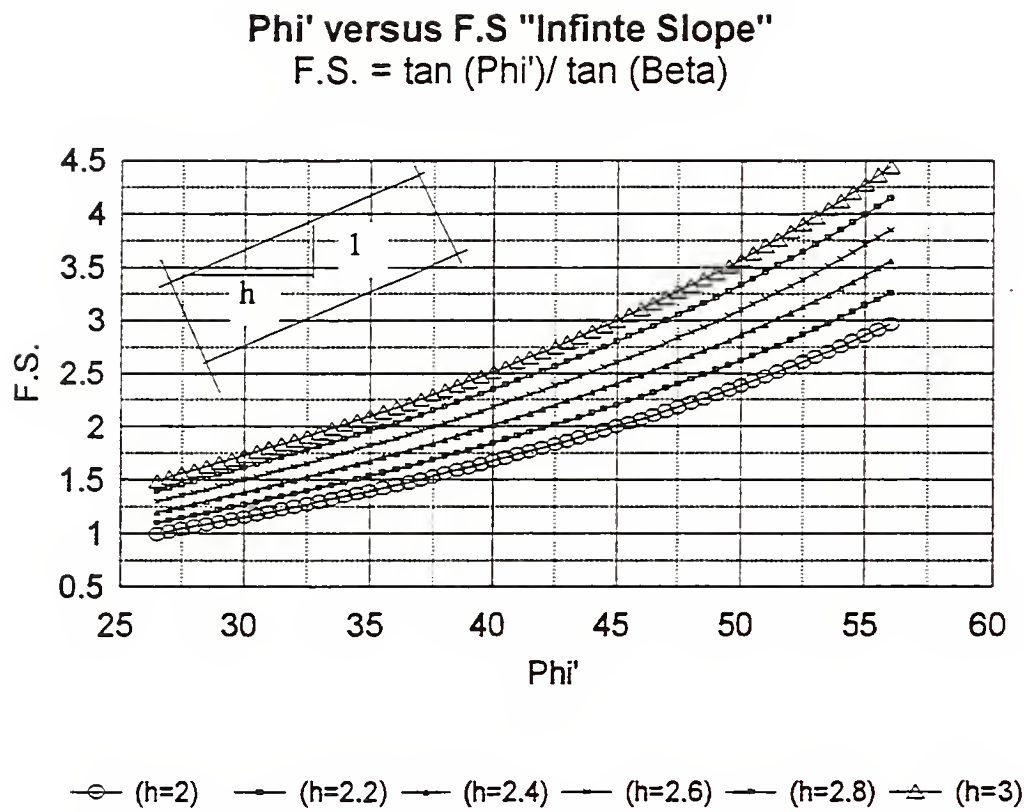

Figure 6.2 Effect of Strength Angle and Slope Angle on the Factor of Safety of an Infinite Slope of Cohesionless Material

may dictate such conditions. The use of a mild slope may be inconceivable and an alternative solution must be pursued.

The limit equilibrium method models the material behavior as a rigid perfectly plastic behavior i.e. no consideration is made for the deformation. However, due to its simplicity, it is widely used. The choice of the angle of shearing resistance must consider the differences between the field conditions and the laboratory conditions. The field shear strength can be different from the shear strength obtained in the laboratory. The techniques for compaction are not similar, even though the relative compactions can be the same. The States of stress on a soil element in the field may also be different from the state of stress on a soil sample in the laboratory.

6.8 Utilization Practices Versus Disposal Practices

According to the results of this research, a mixture that is rich in bottom ash can produce greater shear strength and smaller volumetric changes than a mixture that is rich in fly ash, if both were compacted at the same R% (below 95%). However, if the mixtures are compacted appropriately ($R \geq 95\%$) adequate behaviors can be produced from both bottom ash rich and fly ash rich mixtures. Limiting the use to bottom ash rich mixtures only, can have significant impact on the potential for ash utilization. The typical ash production ratio is 20 to 30% bottom ash and 80 to 70% fly ash. A significant portion of the bottom ash settles closer to the discharging locations. The mixtures existing near to a current or an old discharge location are typically rich in bottom ash. Accordingly, the fly ash percentage becomes generally prevailing in the majority of co-mingled disposal sites.

A review of the current disposal practices is required. The problem that complicates large volume utilizations is the lack of uniformity of the mixtures at disposal sites. This makes the specifications of construction applicable only on a small window of the existing material and necessitate writing specifications for each job individually. Meanwhile, modifications in the disposal practices can further enhance the quality of the disposed ash and significantly assist the utilization and recycling process. A multi-

disciplinary research is needed to provide alternatives to the current ash disposal techniques.

Several improvements can be applied on the current disposal system. A record containing the positions of discharging locations can be developed. The vicinities of these points normally contain the coarsest mixtures. Geotechnical investigations can be implemented to characterize designated borrow areas. Periodic characterization of the disposal sites can be performed using procedures similar to the ones implemented in this investigation. The data base developed can serve as ready records such that the investigated borrow areas can become candidates for utilization in large volume highway construction projects.

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 Conclusions

The results of this research support the use of environmentally sound coal ash mixtures in building highway embankments. Highway embankments of coal ash mixtures can be beneficial if appropriate design and construction procedures are followed. The material has to pass the appropriate environmental requirements before their use in construction. As the environmental requirements are satisfied, the fly/bottom ash mixtures can provide fill materials of comparable strengths to most granular soils while having the advantage of lesser dry unit weights. Highway embankments can provide a final destination for the ash, while using the coal ash can preserve natural soils that would otherwise be used as embankment materials.

The major difficulty for utilizing coal ash mixtures is the heterogeneity of the mixtures, a result of the current disposal practices. Characterization of the composition of coal ash mixtures is important for the appropriate control of compaction. Small surface samples may not represent the range of mixtures existing in a borrow area. To represent the fine materials in a mixture, the fly ash content may be used in the case of explicit mixtures while for the implicit mixtures the utilization of percent finer than 0.075mm provides a more direct measure of the fines content.

The microscopic investigation shows that changing the fly ash content in the mixture has a significant effect on the mixture behavior. As the fly ash content increases from zero to approximately 25%, the fine fly ash particles gradually mask the rough bottom ash particles surfaces and fill the voids between them. At high fly ash contents (greater than

50%) the bottom ash particles become separated and the mixture behavior is mostly controlled by the fly ash.

Compaction provides an economic method for stabilizing the ash mixtures. The compaction properties of laboratory compacted samples (using ASTM D 698) depend on the ash composition (fly ash content or fines content) and the compaction moisture content. Below an optimum fly ash content, the maximum dry unit weight (γ_{dmax}) increases and the optimum moisture content (w_{opt}) decreases as the fly ash content increases. Conversely, above the optimum ash content, adding fly ash decreases the maximum dry unit weight γ_{dmax} and increases the optimum moisture content w_{opt}.

The degree of compaction (the relative compaction, R%) can be used effectively to control the compaction of a wide range of coal ash mixtures. The dry unit weight of a sample can be determined and the degree of compaction calculated using the compaction curve of a material of similar composition and grain-size distribution. The compaction moisture range and the compaction effort are adjusted so that the minimum value expected for the degree of compaction reaches the target value (e.g., at least 95%).

To control compaction appropriately, a family of compaction curves needs to be constructed for the range of existing mixtures in a power plant. To control field compaction, the relative compaction needs to be checked against a compaction curve for a material with grain-size distribution similar to the field-compacted fill. The compaction moisture range and the compaction effort must be adjusted so that the minimum value expected for the relative compaction (R) reaches the target value (e.g., at least 95%).

Increasing the degree of compaction leads to increasing the peak strength and reducing the volumetric changes during consolidation and shearing. It also enhances the behavior of the material under shear stresses leading to more dilation or tendency to dilation. The peak angle of shearing resistance increases accordingly.

Using the degree of compaction of 95% in the laboratory provided adequate shear strength angles and reduced the compressibility. The degree of compaction at 90% provided

lower peak shear strength and more compressible behavior during shear. It is hence recommended to provide adequate compaction to reach a relative compaction of at least 95% or greater.

The shear strength in terms of ϕ'_{max} or ϕ'_{crit} is a function of the ash mixture composition, the degree of compaction R%, and the confining pressure σ_3'. For slope stability analysis, the design angle of shearing resistance ϕ' needs to be chosen based upon the minimum available angle provided by any of the mixtures within the fill.

In the case of explicit mixtures, the mixture proportion can be controlled to maximize the strength of the fill and optimize ash disposal. The fly ash content in the mixture can be chosen below the optimum fly ash content. The mixture may alternatively be designed to maximize the fly ash disposal, and provide a lighter-weight fill, for example, as desirable if the foundation soils are soft. In such a case it is advisable to include bottom ash contents of 25% or less, in order to produce a more uniform behavior of the mixture.

The composition of implicit mixtures in disposal sites is not uniform, but, the change in texture is usually gradual, and the fines content is usually greater than optimum, except near the vicinity of a discharge point. At the same relative compaction, as the mixtures become rich in fines ($F_2 > 50\%$), the change in the strength angles ϕ' becomes small.

In a dilatant behavior (dense material and moderate to low confinement), the mobilized angle of shearing resistance increases to a peak value then decreases as the axial strains increase from zero. The peak angle increases to a limit as the relative compaction increases. Overcompaction and particle crushing limit the value of the peak angles that can be achieved by increasing the degree of compaction.

At the same strain levels, the mobilized angles decrease as the confining pressure increases and as the fines content increases. After reaching a peak, the strength of dense mixtures that are rich in fines drops rapidly towards an ultimate value, as the axial strain increases. For slope stability analysis, design strength angles need to be chosen such that it

can be achieved by the range of mixtures included in the slope and within the expected range of deformations.

The compacted ash mixtures may exist in a state of partial saturation. The resulting matric suction can lead to increasing the apparent strength, but it is not recommended to apply this increase in the analysis, since its variability cannot be accurately predicted.

The current disposal practices of the coal ash need to be reviewed. New techniques for coal ash disposal need to be developed. Special sedimentation techniques can be applied to improve the homogeneity of the ash mixtures in disposal sites.

7.2 Recommendations

Data from field tests and embankment demonstration projects need to be combined with results of this study to provide more insight into the problem. Correlations may be developed between field compaction and laboratory compaction, as sufficient data are accumulated.

Composition characterizations and families of compaction curves need to be constructed for power plants that are interested in large volume utilization of mixtures.

New methods need to be developed for controlling and engineering the disposal process of coal ash in the power plants need. The discharging and deposition process can be designed aiming at more homogenous composition of the materials in the disposal sites.

New quick methods for compaction control are needed. Methods such as index tests (simple penetrometers) need to be investigated. Utilization of quick methods for determining the moisture content and dry unit weight (e.g., time domain reflectometry) can accelerate the results and need to be explored.

New techniques are needed for accelerating the soil drying and fines content determination. For an appropriate control of the compaction of ash mixtures, the mixture

composition needs to be determined. The traditional techniques are time consuming. The development of new techniques can accelerate construction.

Dynamic behavior of loose ash deposits in disposal ponds should be studied to mitigate the hazards of ground shaking and failures of pond boundaries in power plants. The ash mixtures are deposited in a loose to very loose condition, as hydraulic fill. The moisture content and void ratio of these unstabilized materials are typically high. This leads to significant instability as they become disturbed by deformation or vibration.

Numerical methods may be applied to model the stress strain behavior of embankments of explicit mixtures. The explicit mixtures can be composed in a relatively controlled- process. The stress strain behavior of the embankment and foundation soils can then be modeled using numerical methods.

Approved anti dusting materials or water needs to be used where dusting is anticipated during construction.

As a long term plan, based on progressively successful use of the fly/bottom ash mixtures, improved disposal procedures can be developed and improved such that controlled mixtures can be produced and utilized more reliably. In such conditions, the power plants can benefit from long term contracts of coal ash utilization instead of the current one-project basis. The INDOT specifications for construction can also be simplified accordingly.

LIST OF REFERENCES

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Notes:

ASCE	= American Society of Civil Engineers
AASHTO	= American Association of State Highway and Transportation Officials
ASTM	= American Society for Testing and Materials
EIA	= Energy Information Administration
ENR	= Engineering News Record
EPA	= Environmental Protection Agency
EPRI	= Electric Power Research Institute
FHWA	= Federal Highway Administration
IAC	= Indiana Administrative Code
INDOT	= Indiana Department of Transportation
TRB	= Transportation Research Board
TRR	= Transportation Research Record
US	= The United States
USDOC	= U S Department of Commerce
USIFCAU	= The University of Southern Indiana Forum for Coal Ash Utilization

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Appendix
INDOT Special Provisions For Embankments Constructed of Coal Combustion By-Products

First Project: US 12/Over Kennedy Ave.

Embankments Constructed of Bottom Ash Coal Combustion By-Products

DESCRIPTION. This work shall consist of using coal combustion by-products as borrow or B borrow material if such by-products are in accordance with Indiana Department of Environmental Management's and the Department's requirements as described herein. This material shall not be used as backfill for the reinforced earthwall.

MATERIALS. Coal combustion by-products include fly ash, bottom ash, or boiler slag produced by coal-fired electrical or steam generating units. Fly ash, bottom ash, and boiler slag shall be restricted to type IV and type 111. Such by-products may be type II if the pH is between *5* and 10 as defined by *329* IAC *2-9-3.* The following table shall be used to determine the type of coal combustion by-products. Type I by-products will not be permitted.

The material to be used shall be bottom ash. Such material shall be in accordance with 203.08 for borrow or 211 for B borrow. Bottom ash by-product type III shall be obtained from the R. M. Schahfer Power Plant in Jasper County. Sampling and testing data show that Schahfer ponded bottom ash is a type III by-product as defined by *329* IAC *2-9-3.*

Figure I shown on the plans shows the S pond sampling locations at Schahfer Power Plant. Based on the test results, only materials near sampling locations S-3 and S-4 shall be used. Bottom ash may be supplied dry or in a moist condition in covered dump trucks.

INDIANA ADMINISTRATIVE CODE
RESTRICTED WASTE SITETYPE CRITERIA

PARAMETER	CONCENTRATIONS (milligrams 1per liter)			
	Type IV	Type I I I	Type II	Type I
(a) For Parameters Using the EP Toxicity Test*				
Arsenic	<0.05	<0.5	<1.25	<5.0
Barium	<1	<10	<25	<100
Cadmium	<0.01	<0.1	<0.25	<1.0
Chromium	<0.05	<0.5	<1.25	<5.0
Lead	<0.05	<0.5	<1.25	<5.0
Mercury	<0. 002	<0.02	<0.05	<0.2
Selenium	<0.01	<0.1	<0.25	<1.0
Silver	<0.05	<0.5	<1.25	<5.0
(b) For Parameters Using the Leaching Method Test				
Barium	<1	<10	<25	**
Boron	<2	<20	<50	**
Chlorides	<250	<2,500	<6,250	**
Copper	<0.25	<2.5	<6.25	**
Cyanida, Total	<0.2	<2	<5	**

Flouride	<1.4	<14	<35	**
Iron	<1.15	<15	<**	**
Manganese	<0.05	<0.5	<**	**
Nickel	<0.2	<2	<5	**
Phenols	<0.3	<3	<7.5	**
Sodium	<250	<2,500	<6,250	**
Sulfate	<250	<2,500	<6,250	**
Sulfide, Total	<1***	<5	<12.5	**
Total Dissolved Solids	.<500	<5,000	<12,500	**
Zinc	<2.5	<25	<62.5	**
pH (Standard Units)	6 - 9	5 - 10	4 – 11	**

* The Indiana Department of Environmental Management will permit EP toxity test or TCLP test.
** Testing will not be required.
*** If detection limit problems exist, the Indiana Department of Environmental Management's office of Solid and Hazardous Waste shall be consulted for guidance.

CONSTRUCTION REQUIREMENTS

ON-SITE STORAGE. Bottom ash may be stored in silos, pneumatic tank trucks, or bins, or stockpiled on site.

DUST CONTROL. Adequate measures shall be taken during construction to control dust. Spraying with water, limewater, bituminous sprays, or other sealing 'sprays will be considered to be acceptable methods for dust control.

SITING CRITERIA.Siting criteria will not apply to typeIV by-products as defined by 329 IAC-2-9-3. However, bottom ash type III to be used to construct highway embankments or other structural fills shall not be placed as follows:

(a) Within 3 vertical feet (0.9 m) of the seasonal high water table, unless an adequate drainage system is provided to prohibit saturation of the coal combustion by-products. A zone of compacted soil may be placed at the base of the embankment or structural fill to achieve the required separation distance.

(b) Within 100 horizontal feet (30 m) of a perennial stream, drainage channel, lake or reservoir, unless the embankment or structural fill is protected by a properly engineered diversion or structure that is approved by the Department.

(c) Within 300 horizontal feet (91 m) of a well, spring, or other ground water source of potable water, unless it can be demonstrated and approved by Indiana Department of Environmental Management that no ground water degradation will occur.

(d) Within a wetland, floodplain, or other protected environmental resource area, unless appropriate approvals are obtained from the Federal, State, or local agency having jurisdiction.

(e) Within areas of karst topography or over mines, unless it is demonstrated that the integrity of the embankment will not be damaged by subsidence.

PLACEMENT AND COMPACTION. The placement and compaction of bottom ash by-product shall be performed in accordance with 203.23 except as follows:

(a) Bottom ash shall be compacted to at least 95 percent of the maximum dry density, at a moisture content between -3 to –7 percentage points of optimum moisture *content. Bottom* ash shall not be placed at moisture *content in* excess of -3 percentage points of optimum moisture *content.*

(b) Moisture and density tests shall be performed so that the required density is achieved throughout the embankment. Frequency of testing shall be performed in accordance with the Department's Frequency Manual. The laboratory and field density determination shall be made in accordance with 203.24.

PROTECTION OF METAL AND CONCRETE APPURTENANCES. Type II coal combustion by-products may be corrosive to metal structures or may contribute to the deterioration of concrete by sulfate attack. For situations for which corrosive attack is a *concern, the* embedded materials shall be provided with cathodic protection, bitumen, polymer, or other protective coatings, or shall be provided with a substitute fill material in the contact areas, as appropriate. However, based on the test results, type III bottom ash will not be.considered as corrosive to metal structures.

WEATHER RESTRICTION. Bottom ash may be placed during *inclement* weather conditions if placement procedures are adjusted to provide compaction and moisture control.

(a) A thin frozen layer of less than 2 inches (50 mm) at the surface may be broken, blended in-place with fresh material, and recompacted. operations shall be suspended if this procedure is not effective, if water freezes during compaction, or if the temperature falls below 20 F (-7 C) for 48 consecutive hours.

(b) If freezing temperatures continues for 48 hours, the affected layer of material shall be removed. Such material shall not be incorporated into the fill until thawing occurs. The material shall return to a moisture content of -3 to -7 percent, so that it may be compacted in accordance with 203.23.

(c) Compaction of bottom ash may proceed during wet weather if the required density is achieved.

COVER MATERIAL. Coal combustion by-products shall be covered or sealed with a minimum of 2 feet (0.6 m) of cohesive soil, finished pavement, or other structure. Cohesive soil (as described below) encasement shall be placed and compacted at the same time as the bottom ash lift. All cover materials shall be appropriately seeded and vegetated in accordance with 203.09.

The soil used for the *encasement shall* be "clay" or "silty" ("A-6" or "A-7-6") as classified under INDOT Standard Specification Section 902.1. This means that the soil particles must be more than 30% (by weight) smaller than 0.002 mm and less than 50% larger than .075 mm (by weight).

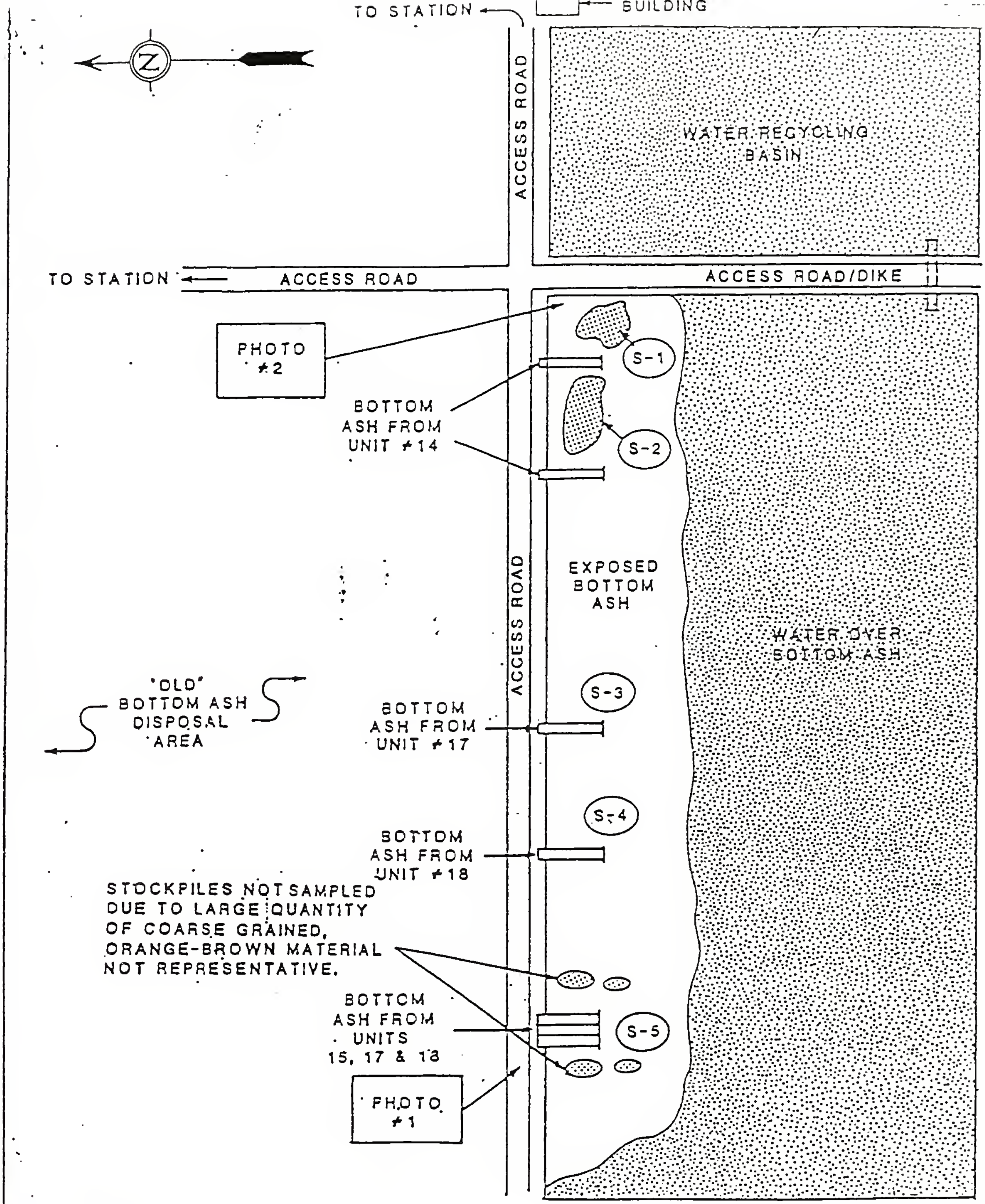
METHOD OF MEASUREMENT. Bottom ash embankment and encasement will be measured by the cubic yard (cubic meter).

BASIS OF PAYMENT. Bottom ash embankment will be paid for at the contract unit price per cubic yard (cubic meter) placed and compacted. Encasement material will be paid for at the contract price per cubic yard (cubic meter) furnished and compacted in place.

Payment will be made under:

Pay Item	Pay Unit
Embankment, Bottom Ash	Cubic Yard (Cubic Meter)
Encasement Material	Cubic Yard (Cubic Meter)

The bottom ash shall be supplied to the project site by the R. M. Schahfer Power Plant at no cost to the Contractor or the Department.



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SKETCH OF WASTE DISPOSAL AREA WITH SAMPLING LOCATIONS AND OBSERVATIONS SCHAHFER GENERATING STATION	DWN. LDA	CHKD. DAG
	APPD. NJB	DATE 4/19/93
NORTHERN INDIANA PUBLIC SERVICE CO. HAMMOND, INDIANA	SCALE: N.T.S.	
	DRAWING NUMBER 93-114-A1	REV

FIGURE 1

Second Project: 1-465/56th Street, Marion County, Indianapolis

EMBANKMENTS CONSTRUCTED OF COAL COMBUSTION BY-PRODUCTS

DESCRIPTION: This work shall consist of using coal combustion by-products (C.C.B.P.1s) as borrow or B borrow material if such by-products are in accordance with Indiana Department of Environmental Management's and the Departments requirements as described herein. This material shall not be used as backfill for the reinforced earthwall (if proposed).

MATERIALS: Coal combustion by-products include fly ash, bottom ash, or boiler slag produced by coal-fired electrical and/or steam generating units. Fly ash, bottom ash, and boiler slag shall be restricted to type IV and type 111. Such by-products may be type II if the pH is between 5 and 10 as defined by 329 IAC 2-9-3. The following table shall be used to determine the type of the coal combustion by-products. Type I by-products shall not be permitted.

The material to be used shall be a combination of fly ash and bottom ash. Such material shall be in accordance with 203.08 for borrow or 211 for B borrow. Coal combustion by-product type III shall be obtained from the E. W. Stout Generating Station in Indianapolis. Sampling and testing data show that Stout Ponded C.C.B.P.19 are a type III by-product as defined by 329 IAC 2-9-3.

Figure I as attached shows the sampling locations at Stout Generating Station. Based on the test results, only materials near sampling locations TP-1 and TP-2 shall be used. C.C.B.P. fill shall be taken from the upper 31 of the ash pond. Ash shall be supplied dry or in a moist condition on covered dump trucks.

INDIANA ADMINISTRATIVE CODE
RESTRICTED WASTE SITE TYPE CRITERIA

PARAMETER	CONCENTRATIONS (milligrams per liter)			
	Type IV	Type III	Type II	Type I
(1) For Parameters Using the EP Toxicity Test:*				
Arsenic	<0.05	<0.5	<1.25	<5.0
Barium	<1	<10	<25	<100
Cadmium	<0.01	<0.1	<0.25	<1.0
Chromium	<0.05	<0.5	<1.25	<5.0
Lead	<0.05	<0.5	<1.25	<5.0
Mercury	<0.002	<.02	<0.05	<0.02
Selenium	<0.01	<0.1	<0.25	<1.0
Silver	<0.05	<0.5	<1.25	<5.0
(2) For Parameters Using the Leaching Method Test:				
Barium	<I	<10	<25	**
Boron	<2	<20	<50	**
Chlorides	<250	<2,500	<6,250	**
Copper	<0.25	<2.5	<6.25	**
Cyanida, Total	<0.2	<2	<5	**

Flouride	<1.4	<14	<35	**
Iron	<1.5	<15	<**	**
Manganese	<0.05	<0.50	<**	**
Nickel	<0.2	<2	<5	**
Phenols	<0.3	<3	<7.5	**
Sodium	<250	<2,500	<6,250	**
Sulfate	<250	<20,500	<6,250	**
Sulfide, Total	<J***	<5	<12.5	**
Total Dissolved Solids	<500	<5,000	<12,500	**
Zinc	<2.5	<25	<62.5	**
pH (Standard Units)	6 - 9	5 - 10	4 – 11	**

* The Indiana Department of Environmental Management will permit EP toxity test or TCLP test.

** Testing will not be required.

*** If detection limit problems exist, the Indiana Department of Environmental Management's Office of Solid and Hazardous Waste shall be consulted for guidance.

CONSTRUCTION REQUIREMENTS

ON-SITE STORAGE. C.C.B.P.'S shall be stored in silos, pneumatic tank trucks, or bins, or stockpiled on site.

DUST CONTROL. Adequate measures shall be taken during construction to control dust. Spraying with water, limewater, bituminous sprays, or other sealing sprays will be considered to be acceptable methods for dust control.

SITING CRITERIA. Siting criteria shall not apply to type IV by-products as defined by 329 IAC-2-9-3. However,.coal combustion by-products type III to be used to construct highway embankments or other structural fills shall not be placed as follows:

(a) Within 3 vertical feet (0.9 m) of the seasonal high water table, unless an adequate drainage system is provided to prohibit saturation of the coal combustion by-products. A zone of compacted soil shall be placed at the base of the embankment or structural fill to achieve the required separation distance.

(b) Within 100 horizontal feet (30 m) of a perennial stream, drainage channel, lake or reservoir, unless the embankment or structural fill is protected by a properly engineered diversion or structure that is approved by the Department.

(c) Within 300 horizontal feet (91 m) of a well, spring, or other ground water source of potable water, unless it can be demonstrated and approved by Indiana Department of Environmental Management that no ground water degradation will occur.

(d) Within a wetland, floodplain, or other protected environmental resource area, unless appropriate approvals are obtained from the Federal, State, or local agency having jurisdiction.

(e) Within areas of karst topography or over mines, unless it is demonstrated that the integrity of the embankment will not be damaged by subsidence.

LOCATION. -C. C. B. P.'s shall be placed f rom station 18+00 TO station 28+00 on the left side.

PLACEMENT AND COMPACTION. The placement and compaction of coal combustion by-product shall be performed in accordance with 203.23 except as follows:

Coal combustion By-Products (C.C.B.P.1s) shall be compacted using an approved vibratory steel wheel roller.

The minimum total compactive effort for the vibratory steel wheel roller shall be 47,000 pounds. Total compactive effort is defined as that portion of the static weight acting upon the unsprung compaction drum added to the centrifugal force provided by that drum. If the manufacturer's charts do not list the static weight acting upon the compaction drum, the roller shall be satisfactorily weighed, the weight shall be added to the centrifugal force, and the roller rated in accordance with the Construction Industry Manufacturers Association (CIMA).

Unless otherwise approved in writing, each embankment lift shall receive a minimum of 3 passes with the static roller and a minimum of 2 additional passes. The additional passes shall be made with a static or a vibratory roller as directed by the Engineer. The material shall be bladed before using the vibratory or static roller. A pass shall be in accordance with 401.12. The rollers shall not exceed 3 miles per hour during these passes. The compaction or rolling shall start at the edges and progress towards the center of the embankment.

During compaction, the moisture content of the C.C.B.B.'s shall be maintained between 10% and 15%. Prior to compaction, the C.C.B.P.'s shall be placed in 8 inch (200 mm) loose lifts. No payment will be allowed for any water required for compaction. Nuclear gauges should not be used to measure moisture content unless a new calibration curve is made for C.C.B.P.1s.

Each lift of the encasement material shall be placed and compacted simultaneously with a lift of C.C.B.P.'s. Encasement material shall be placed in accordance with Section 203.23 of the Standard Specifications.

C.C.B.P.18 shall contain a minimum of 60% bottom ash. The C.C.B.P.Is shall come f rom the area of TP-1 and TP-2, northeast of the power lines as shown in the included plan view of Ash Pond No. 1.

Surface drainage onto the site from offsite sources must be diverted to prevent excess water from entering the site during construction.

PROTECTION OF METAL AND CONCRETE APPURTENANCES. Type II coal combustion by-products may be corrosive to metal structures or may contribute to the deterioration of concrete by sulfate attack. For situations for which corrosive attack is a concern, the embedded materials shall be provided with cathodic protection, bitumen, polymer, or other protective coatings, or shall be provided with a substitute fill material in the contact areas, as appropriate. However, based on the test results, type III C.C.B.P.'s will not be considered as corrosive to metal structures.

WEATHER RESTRICTION. C.C.B.P.'s may be placed during inclement weather conditions if placement procedures are adjusted to provide compaction and moisture control.

(a) A thin frozen layer of less than 2 inches (50 mm) at the surface may be broken, blended in-place with fresh material, and recompacted. Operations shall be suspended if this procedure is not effective, if water freezes during compaction, or if the temperature falls below 20 F (-7 C) for 48 consecutive hours.

(b) If freezing temperatures continues for 48 hours, the affected layer of material shall be removed. Such material shall not be incorporated into the fill until thawing occurs. The material shall return to a moisture content of 10 to 15 percent, so that it may be compacted in accordance with 203.23.

(c) Compaction of C.C.B.P.'s may proceed during wet weather if the required density is achieved.

COVER MATERIAL. Coal combustion by-products shall be covered or sealed with a minimum of 2 feet (0.6 m) of cohesive soil. C.C.B.P.'s should not be used within 2 feet (0.6 m) of the pavement section. Cohesive soil (as described below) encasement shall be placed and compacted at the same time as the bottom ash lift. All cover materials shall be appropriately seeded and vegetated in accordance with 203.09.

The soil used for the encasement shall be "clay" or "silty clay" ("A-6" or "A-7-6") as classified under INDOT Standard Specification section 903. This means that the soil particles must be more than 30% (by weight) smaller than 0.002 mm and less than 50% larger than .075 mm (by weight).

LEACHATE MONITORING. Leachates shall be monitored by installing a clay liner with a properly designed and approved leachate collection system under the part of the embankment that shall contain coal combustion by-products. To check background water quality sampling shall be done before placement of any coal combustion by-product. During embankment construction the sampling events shall be more frequent. After construction is complete. sampling shall be done on a quarterly basis at least five years to detect any leachate problems.

The leachate collection system shall be at least 50 ft. (15.33 m) long covering the entire width of the embankment or as specified on the plans.

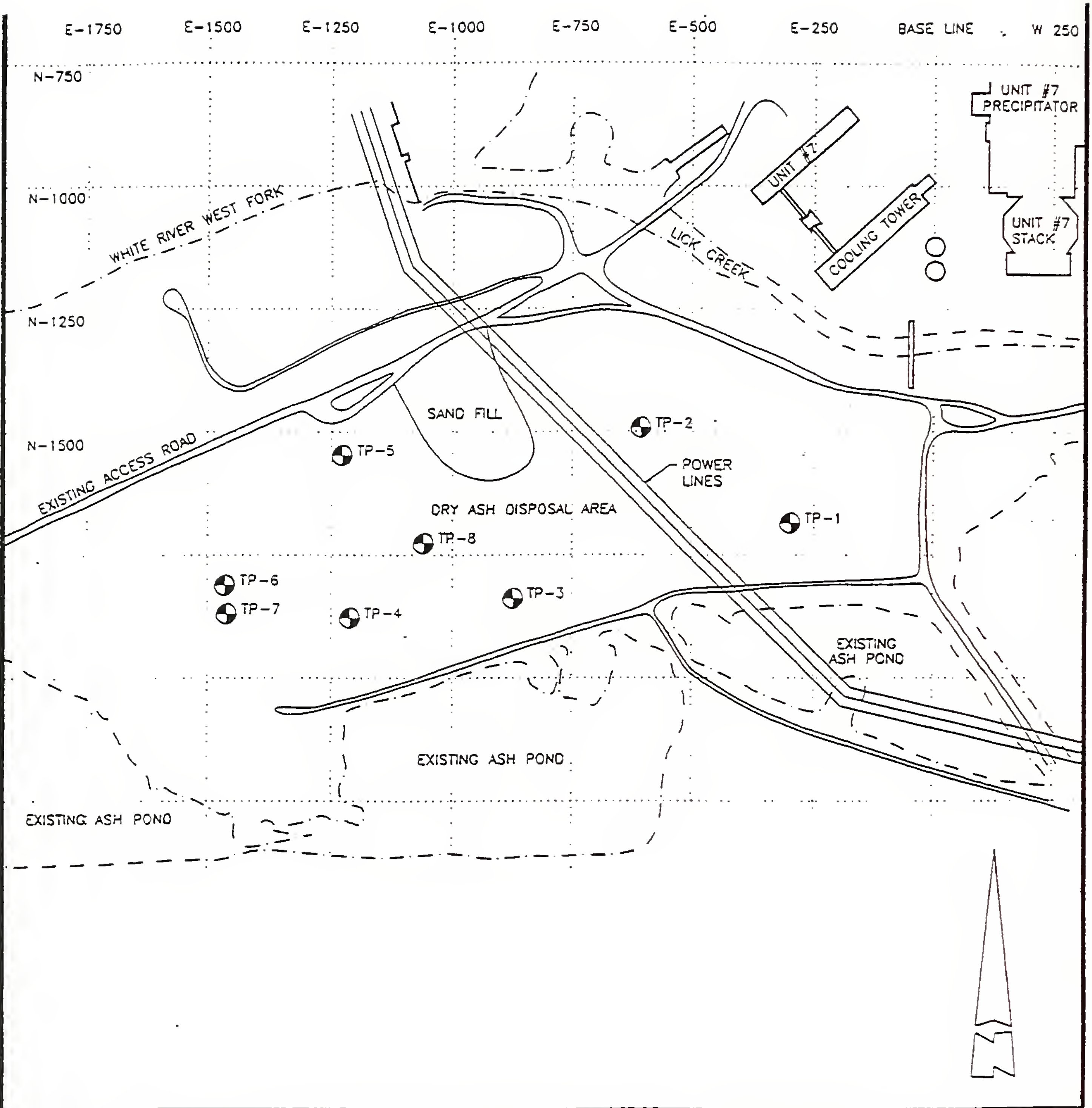
METHOD OF MEASUREMENT. Bottom ash/fly ash embankment and encasement will be measured by the cubic yard (cubic meter).

BASIS OF PAYMENT. C.C.B.P. embankments will be paid for at the contract unit price per cubic yard (cubic meter) placed and compacted. Encasement material will be paid for at the contract price per cubic yard (cubic motor) furnished and compacted in place.

Payment wili be made under:

Pay Item	Pay Unit
Embankment, Bottom/Fly Ash	Cubic Yard (Cubic Meter)
Encasement Material	Cubic Yard (Cubic Meter)
Leachate Collection System	Lump Sum
Leachate Monitoring	Lump Sum

The C.C.B.P.'s shall be supplied to the project site by the E. W. Stout Generating Station at no cost to the Contractor or the Department.



TEST PIT PLAN
ASH POND No. 1
IPL E.W. STOUT GENERATING STATION
INDIANAPOLIS, INDIANA

Project Number:	21-07-94-00231
Scale:	1" = 300'
Figure Number:	2

1994

Third Project: US 50, Knox County

EMBANKMENTS CONSTRUCTED OF COAL COMBUSTION BY-PRODUCTS

DESCRIPTION: This work shall consist of using coal combustion by-products (C.C.B.P.1s) as borrow or 8 borrow material if such by-products are in accordance with Indiana Department of Environmental Management's and the Indiana Department of Transportation's requiremets as described herein. This material shall not be used as backfill for the reinforced earthwall (if proposed).

MATERIALS: Coal combustion by-products include fly ash, bottom ash, or boiler slag produced by coal-fired electrical and/or steam generating units. Fly ash, bottom ash, and boiler slag shall be restricted to type IV and type III. Such by-products may be type II if the pH is between 5 and 10 as defined by 329 IAC 2-9-3. The following table shall be used to determine the type of the coal combustion by-products. Type I by-products shall not be permitted.

The material to be used shall be a combination of f ly ash and bottom ash. such material shall be in accordance with 203.08 for borrow or 211 for B borrow. Coal combustion by-product type III shall be obtained from the E. Cinergy - Gibson Generating Station - Owensville, Indiana. Sampling and testing data show that Gibson co-mingled C. C. B. P. Is are a type I I
by-product as defined by 329 IAC 2-9-3.

Sketch I as attached shows the sampling locations at Gibson Generating Station. Based on the test results, materials from South Ash Pond (location as shown in Sketch 1) shall be used. Ash shall be supplied dry or in a moist condition on covered dump trucks.

INDIANA ADMINISTRATIVE CODE
RESTRICTED WASTE SITE TYPE CRITERIA

PARAMETER	CONCENTRATIONS (milligrams per liter),			
	Type I	Type III	Type II	Type I
(1) For Parameters Using the EP Toxicity Test:*				
Arsenic	<0.05	<0.5	<1.25	<5.0
Barium	<1	<10	<25	<100
Cadmium	<0.01	<0.1	<0.25	<1.0
Chromium	<0.05	<0.5	<1.25	<5.0
Lead	<0.05	<0.5	<1.25	<5.0
Mercury	<0.002	<.02	<0.05	<0.02
Selenium	<0.01	<0.1	<0.25	<1.0
Silver	<0.05	<0.5	<1.25	<5.0
(2) For Parameters Using the Leaching Method Test:				
Barium	<1	<10	<25	**
Boron	<2	<20	<50	**
Chlorides	<250	<2,500	<6,250	**
Copper	<0.25	<2.5	<6.25	**
Cyanida, Total	<0.2	<2	<5	**

Flouride	<1.4	<14	<35	**
Iron	<1.5	<IS	<**	**
Manganese	<O.OS	<0.50	<**	**
Nickel	<0.2	<2	<5	**
Phenols	<0.3	<3	<7.5	**
Sodium	<250	<2,500	<6,250	**
Sulfate	<250	<2,500	<6,250	**
Sulfide, Total	<1***	<5	<12.5	**
Total Dissolved Solids	<500	<5,000	<12,500	**
Zinc	<2.5	<25	<62.5	**
pH (Standard Units)	6 - 9	S - 10	4	**

* The Indiana Department of Environmental Management will permit EP toxity test or TCLP test.
* Testing will not be required.
* If detection limit problems exist, the Indiana Department of Environmental Management's Office of Solid and Hazardous Waste shall be consulted for guidance.

CONSTRUCTION REQUIREMENTS

ON-SITE STORAGE. C.C.B.P.'s shall be stored in silos, pneumatic tank trucks, or bins, or stockpiled on site.

DUST CONTROL. Adequate measures shall be taken during construction to control dust. Spraying with water, limewater, bituminous sprays, or other sealing sprays will be considered to be acceptable methods for dust control.

SITING CRITERIA. Siting criteria shall not apply to type IV by-products as defined by 329 IAC-2-9-3. However, coal combustion by-products type III to be used to construct highway embankments or other structural fills shall not be placed as follows:

(a) Within 3 vertical feet (0.9 m) of the seasonal high water table, unless an adequate drainage system is provided to prohibit saturation of the coal combustion by-products unless otherwise specified by the Geotechnical Section of The Materials and Tests Division.

(b) Within 100 horizontal feet (30 m) of a perennial stream, drainage channel, lake or reservoir, unless the embankment or structural fill is protected by a properly engineered diversion or structure that is approved by the Department.

(c) Within 300 horizontal feet (91 m) of a well, spring, or other ground water source of potable water, unless it can be demonstrated and approved by Indiana Department of Environmental Management that no ground water degradation will occur.

(d) Within a wetland, floodplain, or other protected environmental resource area, unless appropriate approvals are obtained from the Federal, State, or local agency having jurisdiction.

(e) Within areas of karst topography or over mines, unless it is demonstrated that the integrity of the embankment will not be damaged by subsidence.

LOCATION. C.C.B.P.'s shall be placed from station 521+00 TO station 535+00.

PLACEMENT AND COMPACTION. The placement and compaction of coal combustion by-product shall be performed in accordance with 203.23 except as follows:

Coal combustion By-Products (C.C.B.P.'s) shall be compacted using an approved vibratory steel wheel roller.

The minimum total compactive effort for the vibratory steel wheel roller shall be 47,000 pounds (21338 Kg). Total compactive effort is defined as that portion of the static weight acting upon the unsprung compaction drum added to the centrifugal force provided by that drum. if the manufacturer's charts do not list the static weight acting upon the compaction drum, the roller shall be satisfactorily weighed, the weight shall be added to the centrifugal force, and the roller rated in accordance with the Construction Industry Manufacturers Association (CIMA).

Unless otherwise approved in writing, each embankment lift shall receive a minimum of 3 passes with the static roller and a minimum of 2 additional passes. The additional passes shall be made with a static or a vibratory roller as directed by the Engineer. The material shall be bladed before using the vibratory or static roller. A pass shall be in accordance with 401.12. The rollers shall not exceed 3 miles per hour during these passes. The compaction or rolling shall start at the edges and progress towards the center of the embankment.

During compaction, the moisture content of the C.C.B.P.Is shall be maintained between 5% and 9%. Prior to compaction, the C.C.B.P.'s shall be placed in 8 inch (200 mm) loose lifts. No payment will be allowed for any water required for compaction. Nuclear gauges should not be used to measure moisture content unless a new calibration curve is made for C.C.B.P.'s.

Each lift of the encasement material shall be placed and compacted simultaneously with a lift of C.C.B.P.'s. Encasement material shall be placed in accordance with Section 203.23 of the Standard Specifications (for encasement material placement see - sketch II & III).

C.C.B.P.'s shall contain a minimum of 65% bottom ash. The C.C.B.P.'s shall come from the area of South Ash Pond

Surface drainage onto the site from offsite sources must be diverted to prevent excess water from entering the site during construction.

French drains should be installed as shown on plans and be outletted at 1501 intervals.(see sketch II & III)

PROTECTION OF METAL AND CONCRETE APPURTENANCES. Type II coal combustion by-products may be corrosive to metal structures or may contribute to the deterioration of concrete by sulfate attack. For situations for which corrosive attack is a concern, the embedded materials shall be provided with cathodic protection, bitumen, polymer, or other protective coatings, or shall be provided with a substitute fill material in the contact areas, as appropriate. However, based on the test results, type III C.C.B.P.'s will not be considered as corrosive to metal structures.

WEATHER RESTRICTION. C.C.B.P.'s may be placed during inclement weather conditions if placement procedures are adjusted to provide compaction and moisture control.

(a) A thin frozen layer of lose than 2 inches (50 mm) at the surface may be broken, blended in-place with fresh material, and recompacted. Operations shall be suspended if this procedure is not effective, if water freezes during compaction, or if the temperature falls below 20 F (-7 C) for 48 consecutive hours.

(b) If freezing temperatures continues for 48 hours, the affected layer of material shall be removed. Such material shall not be incorporated into the fill until thawing occurs. The material shall return to a moisture content of 5 to 9 percent, so that it may be compacted in accordance with 203.23.

(c) Compaction of C.C.B.P.'s may proceed during wet weather if the required density is achieved.

COVER MATERIAL. Coal combustion by-products shall be covered or sealed with a minimum of 2 feet (0.6 m) of cohesive soil. Cohesive soil (as described below) encasement shall be placed and compacted at the same time as the bottom ash lift. All cover materials shall be appropriately seeded and vegetated in accordance with 203.09.

The soil used for the encasement shall be "cohesive" (clay soils) which meet the requirements of "A-6" or "A-7-6" group of AASHTB 145.

LEACHATE MONITORING. The contractor should be aware that between approximate station 521+00 and approximate station 535+00 several monitoring wells have been installed in the INDOT right of way outside the proposed limits of construction to assess groundwater quality. Wells have been placed on both side (south & north) side of U.S. 50. The wells are conspicuously marked and the contractor shall avoid any work in the area that could damage the wells.

METHOD OF MEASUREMENT. Bottom ash/fly ash embankment and encasement will be measured by the cubic yard (cubic meter).

BASIS OF PAYMENT. C.C.B.P. embankments will be paid for at the contract unit price per cubic yard (cubic meter) placed and compacted. Encasement material will be paid for at the contract price per cubic yard (cubic meter)-furnished and compacted in place.

Payment will be made under:

Pay Item	Pay Unit
Embankment, Bottom/Fly Ash	Cubic Yard (Cubic Meter)
Encasement Material	Cubic Yard (Cubic Meter)

The C.C.B.P.'s shall be supplied to the project site by the Gibson Generating Station at no cost to the Contractor or the Department.

Notes:

Prior to the award of the contract, the successful low bidder shall provide documentation to the Department's Legal Section demonstrating that appropriate arrangements have been made between the Gibson Generating Station and the contractor to:

* secure approved CCBP's and delivery of the required amount/quality at a rate acceptable to the contractor at no cost to the contractor or Department

* address the possible return of small quantities of unused CCBP at no cost to the contractor or Department

* address possible union and subcontractor issues involved in the delivery/return of the CCBP

* If suitable CCBP cannot be acquired or a satisfactory agreement approved, the contractor shall be directed to substitute approved borrow in place of CCBP borrow. Payment shall be at the established contract unit price for borrow.

Special Notification:

The Vincennes Construction Department will advise the following individuals of the time and place of the preconstruction conference: Athar Khan (317-232-5280) of INDOT - Division of Materials and Tests, Richard Marsan of Cinergy Corporation (513-787-3446).